Comprehensive Kernel Instrumentation via Dynamic Binary Translation

Peter Feiner

Angela Demke Brown

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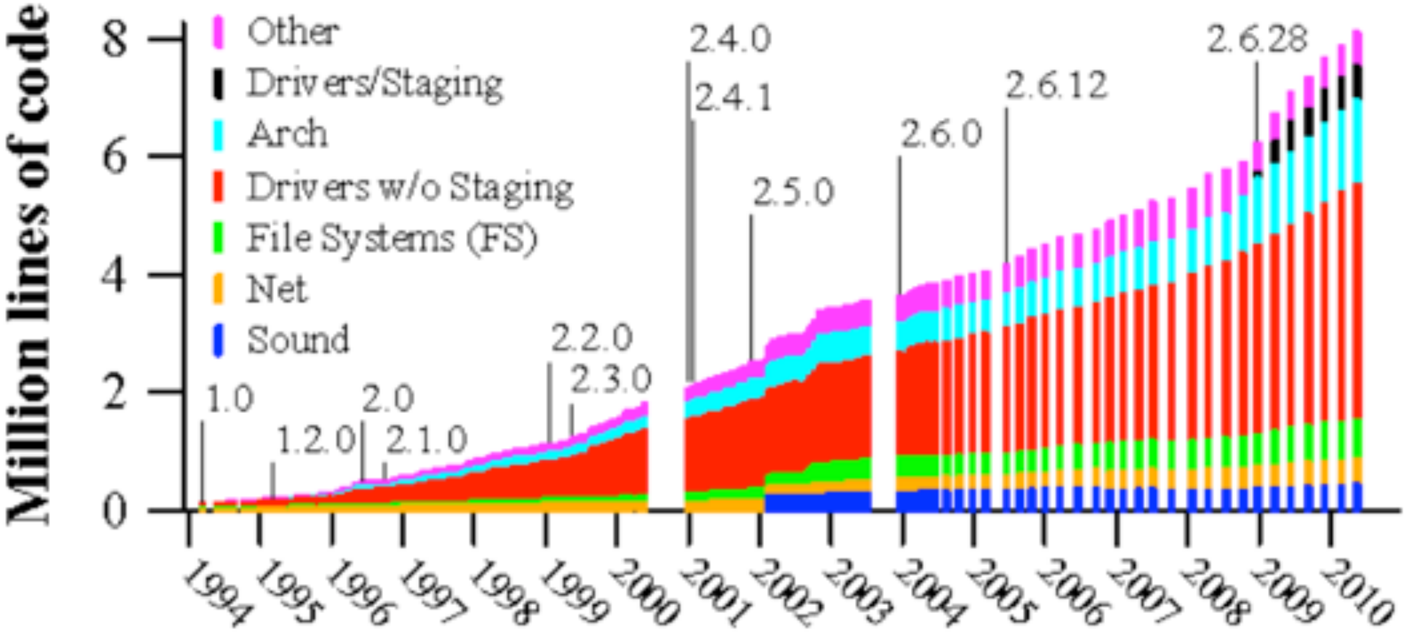
University of Toronto

Complexity of Operating Systems



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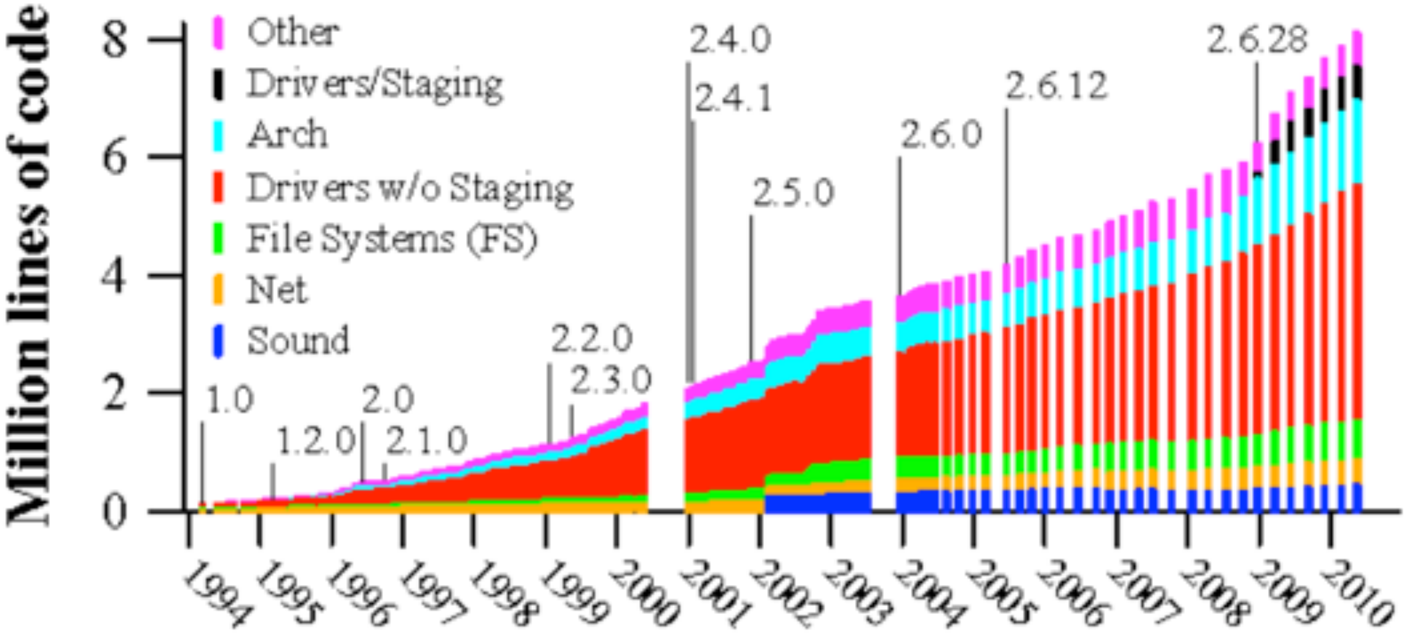
Growth in code size

- Palix, ASPLOS 2011
- Many new drivers!



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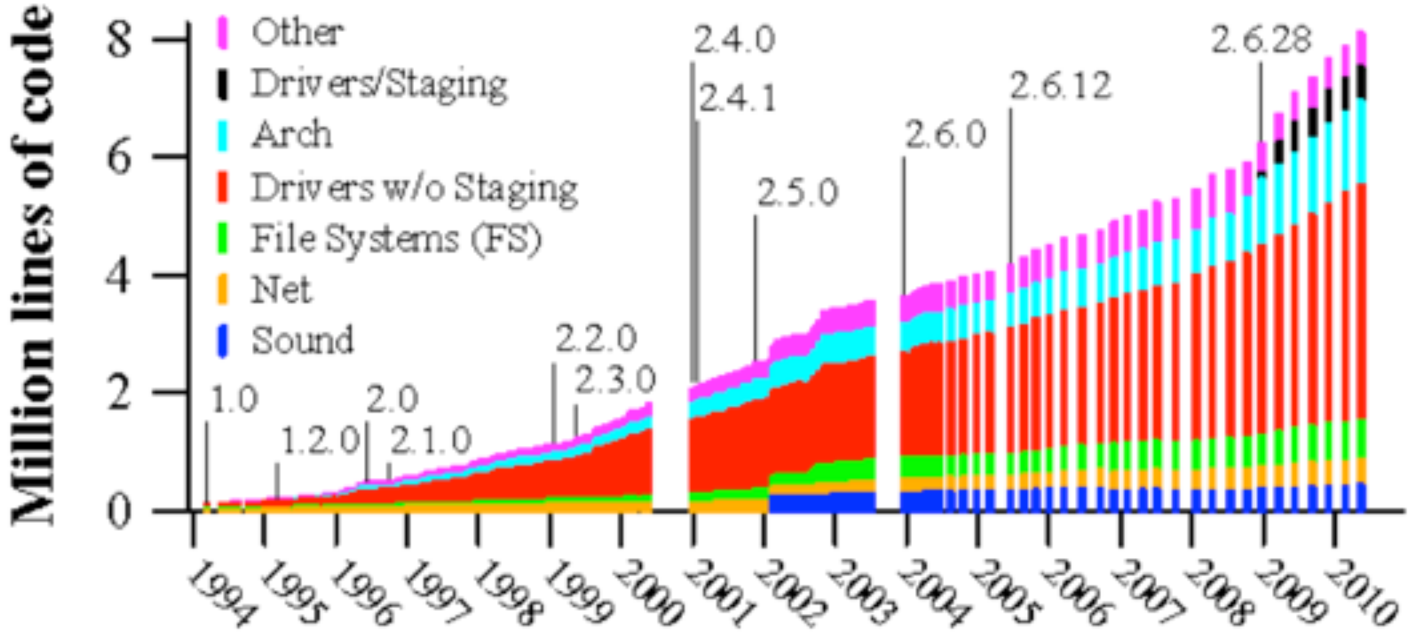
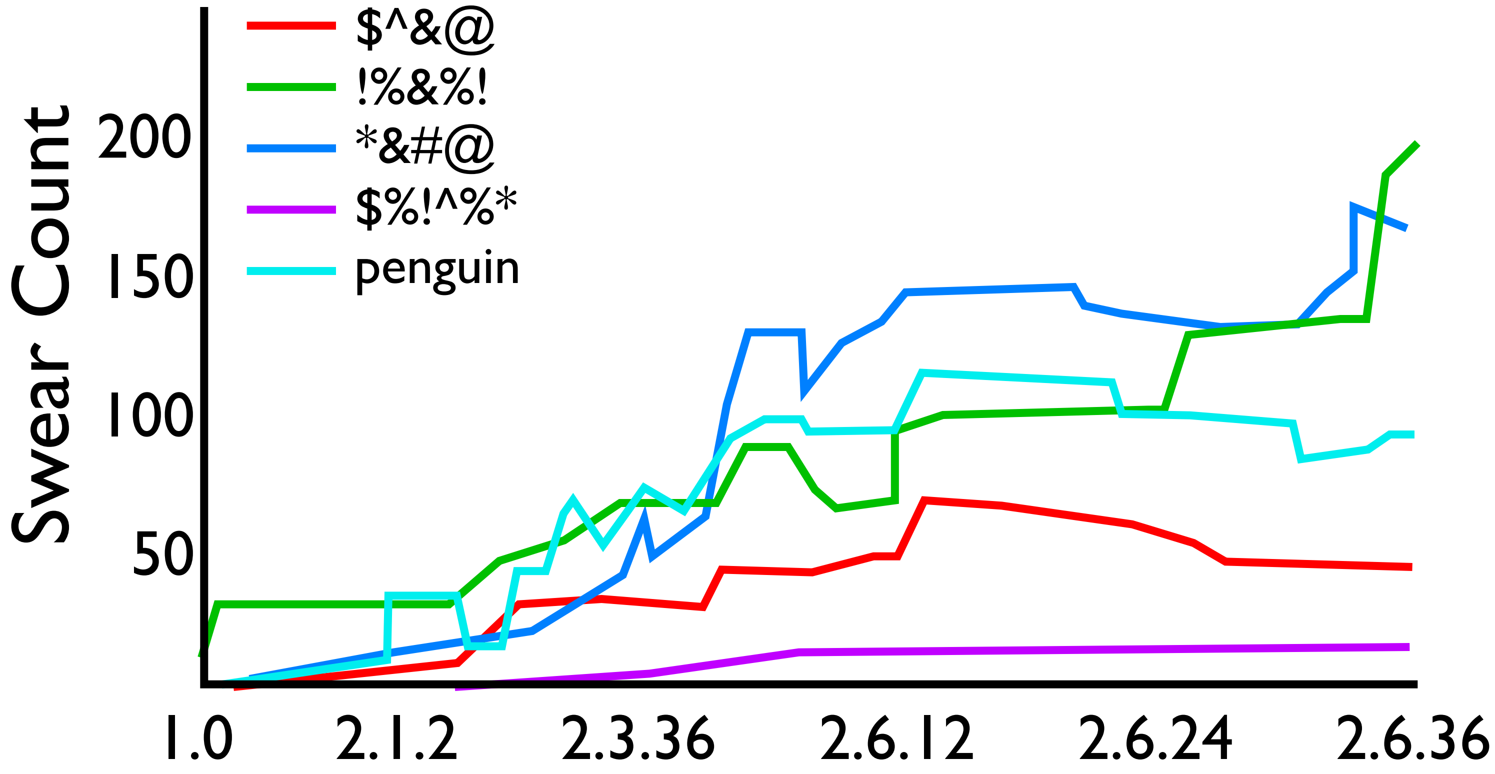


More swearing

- Vidar Holen, 2012



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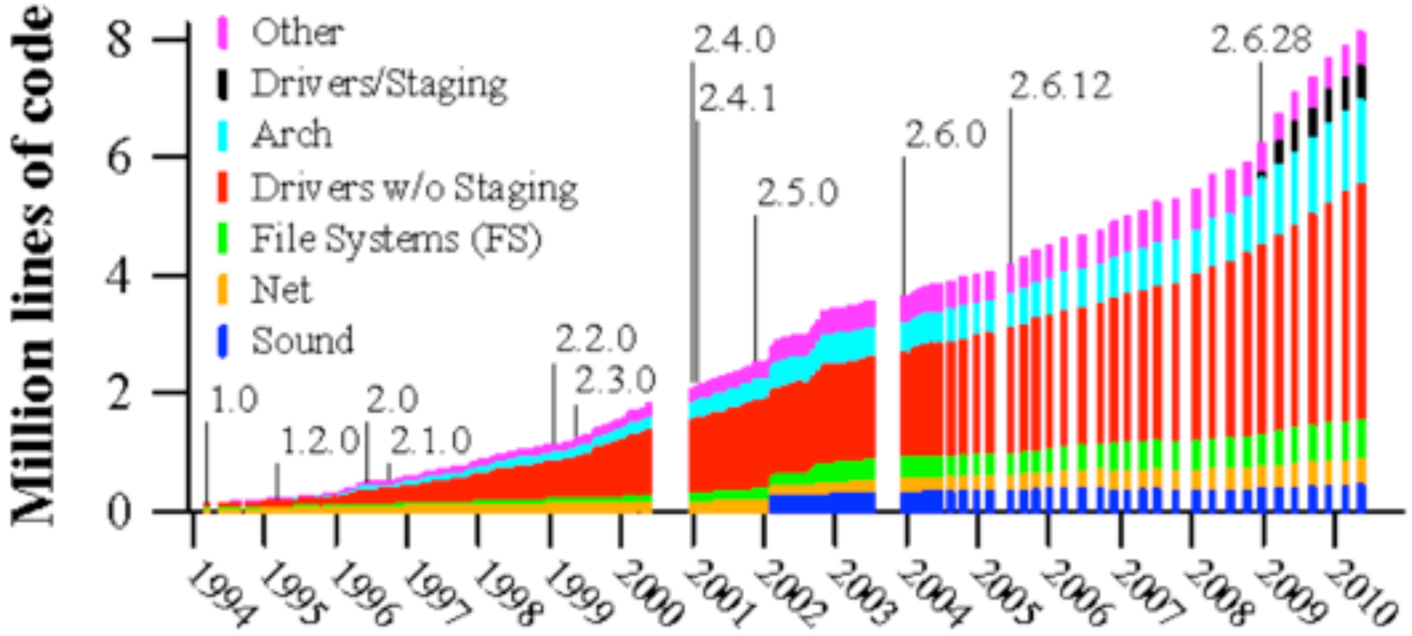

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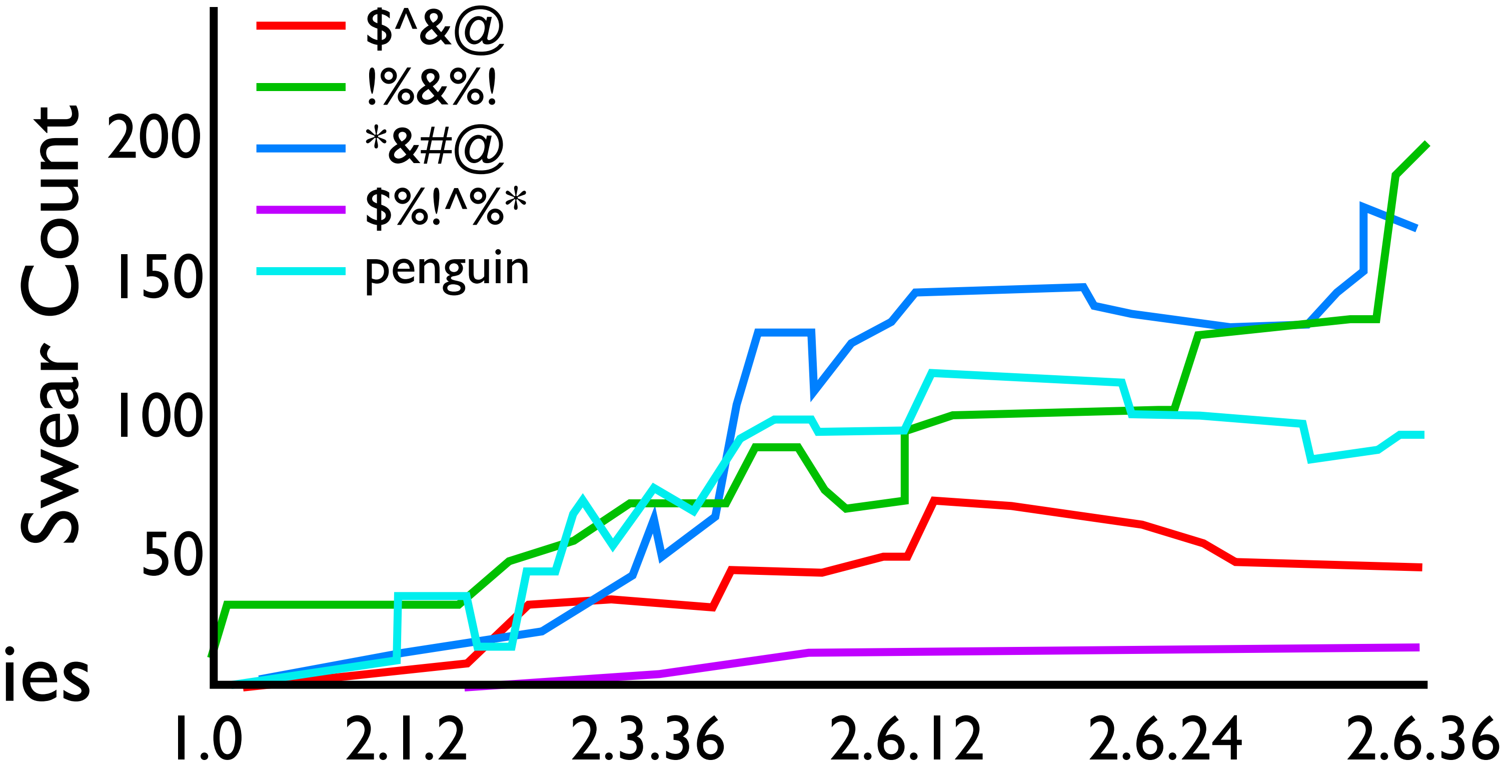
Bugs are inevitable!

- Need coping strategies



Tools would be nice

Awesome tools for **user** code

- Memcheck
- Program Shepherding

Use Dynamic Binary Translation (DBT)

- Rewrite binaries as they execute
- No need for source

Frameworks make building DBT tools easy

- DynamoRIO, Valgrind, Pin

No framework for **OS** code

Our Framework

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Practical

- One author ran system on her desktop for 1 month

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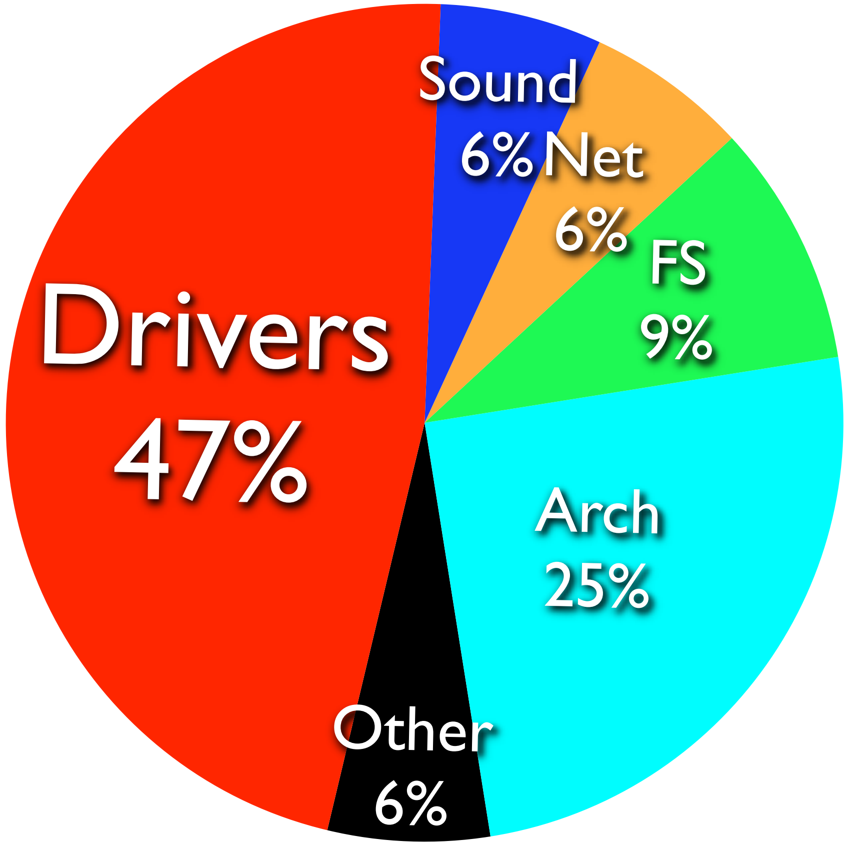

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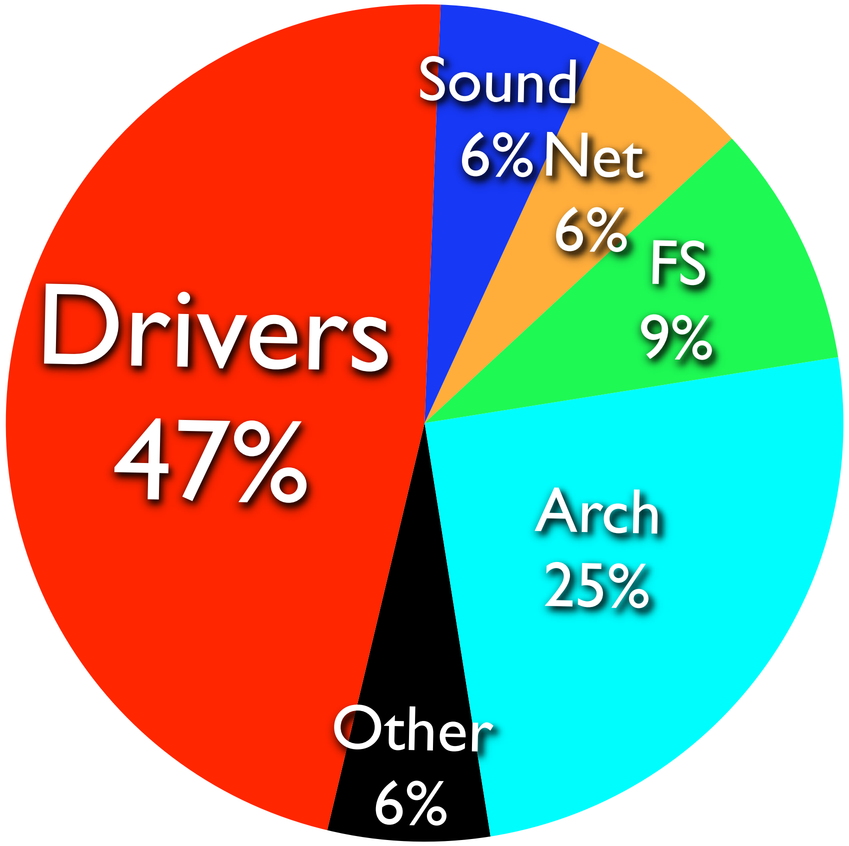

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So add DBT to a hypervisor with pass-through devices?

- Then you'd have the problems we show you how to solve
- ... problems with interrupts!

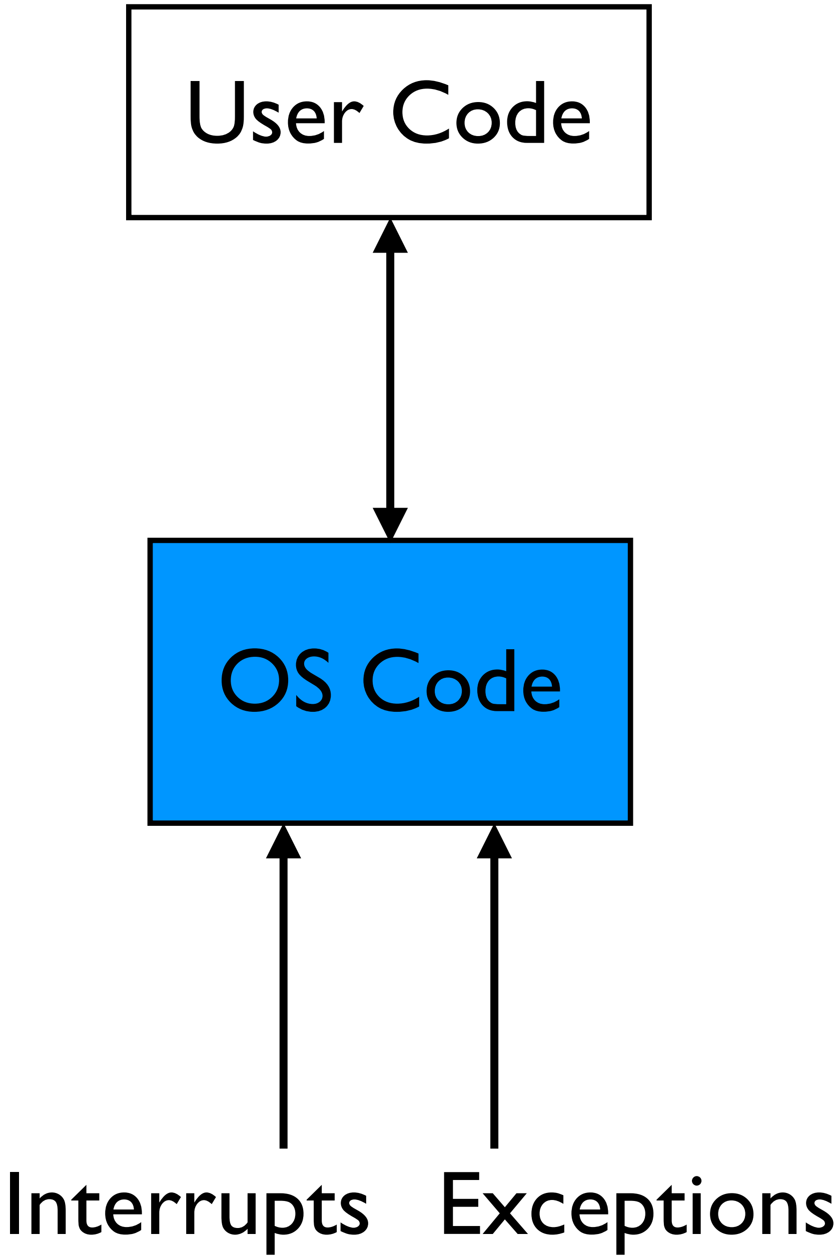
Framework Overview

1. Boot normally

2. Take over

3. JIT the OS

x86 → instrumented x86



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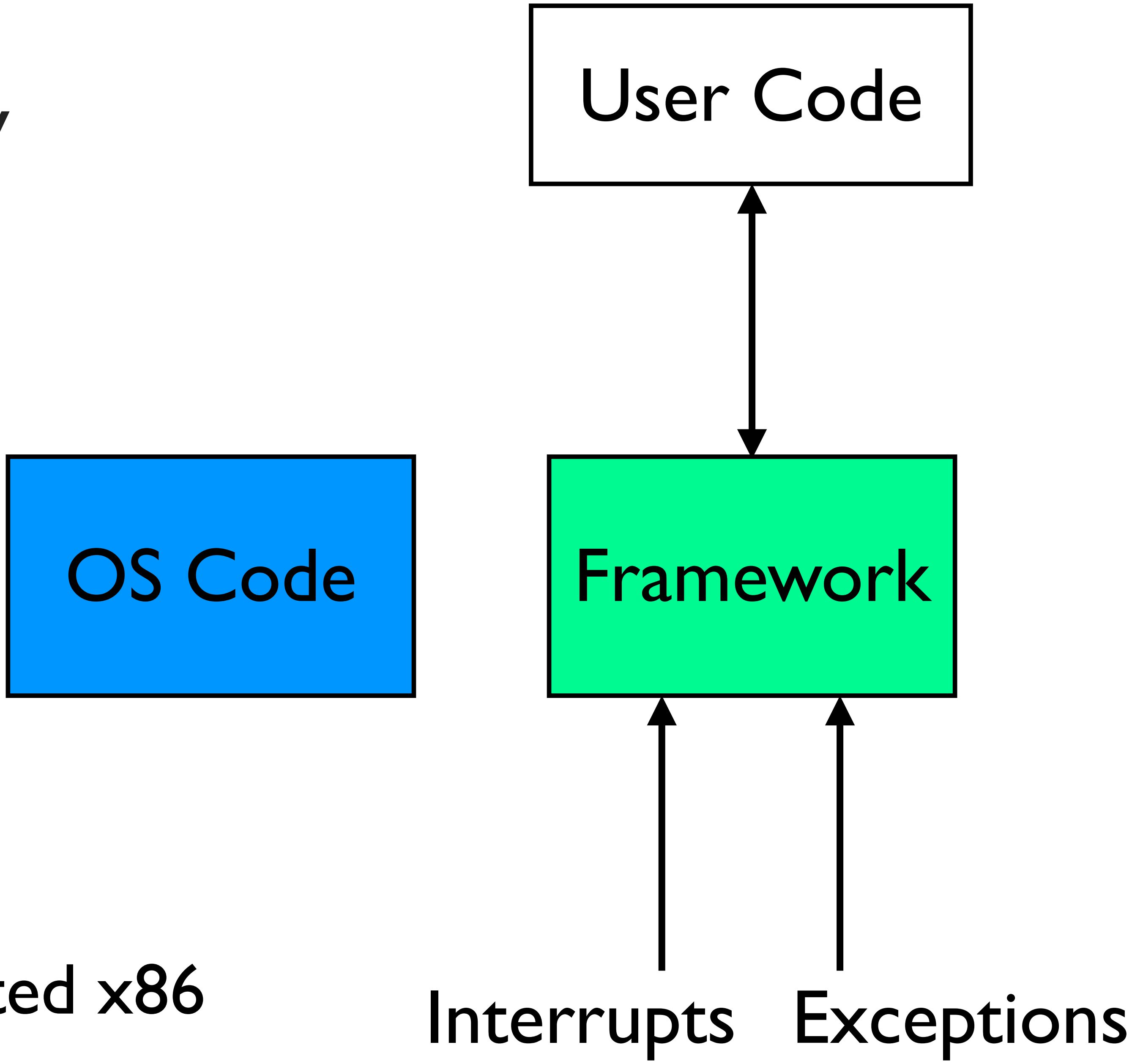

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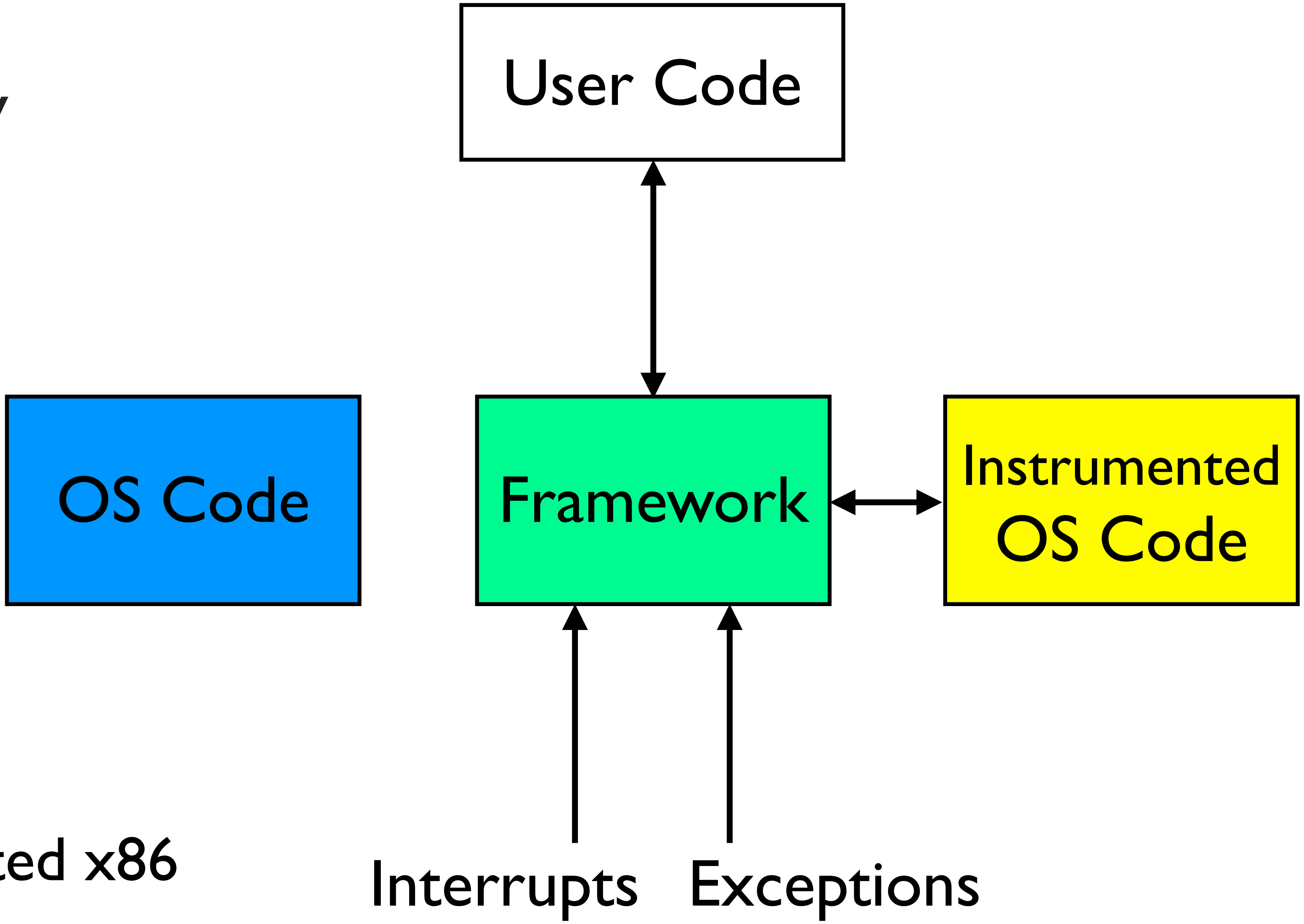

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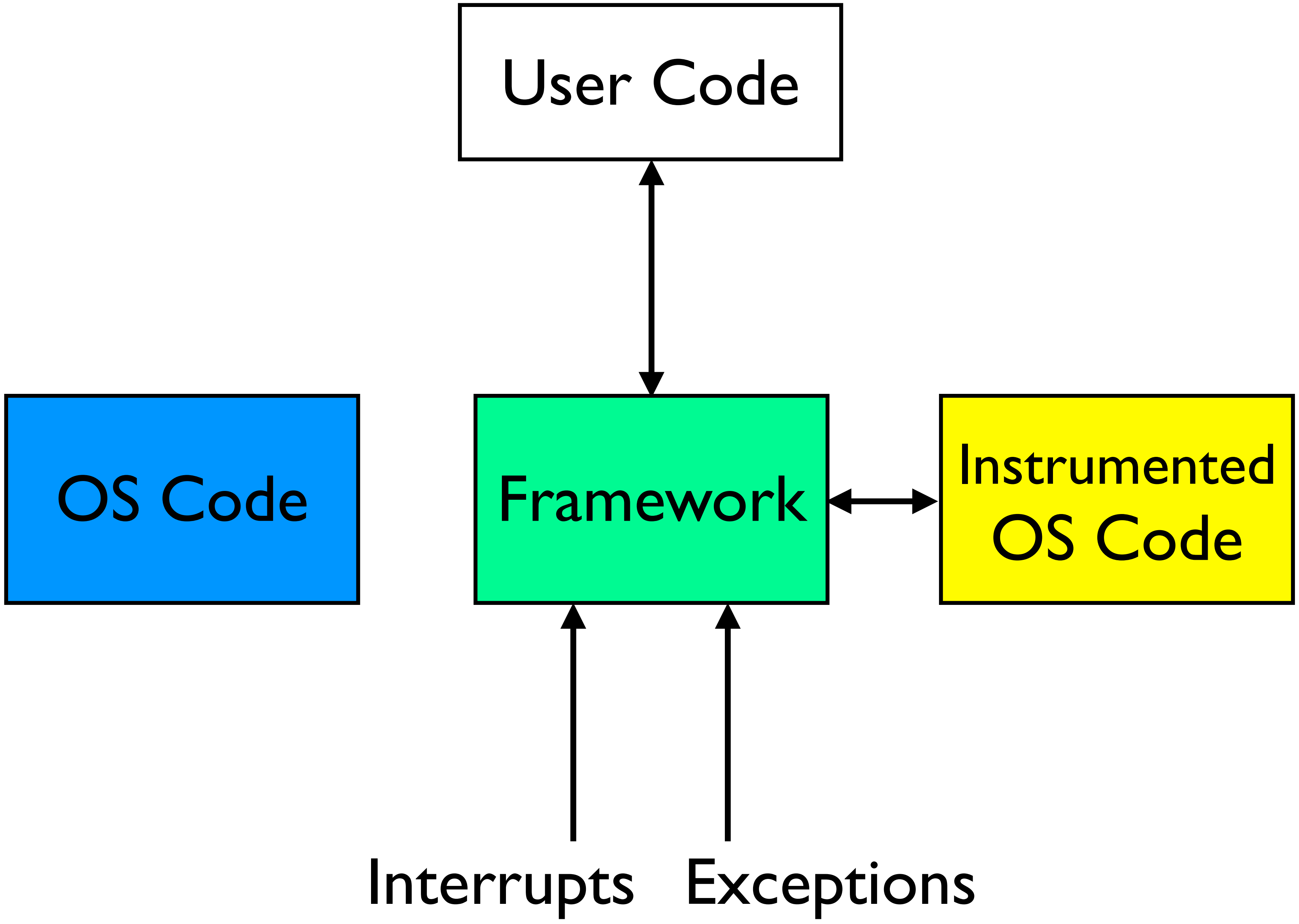

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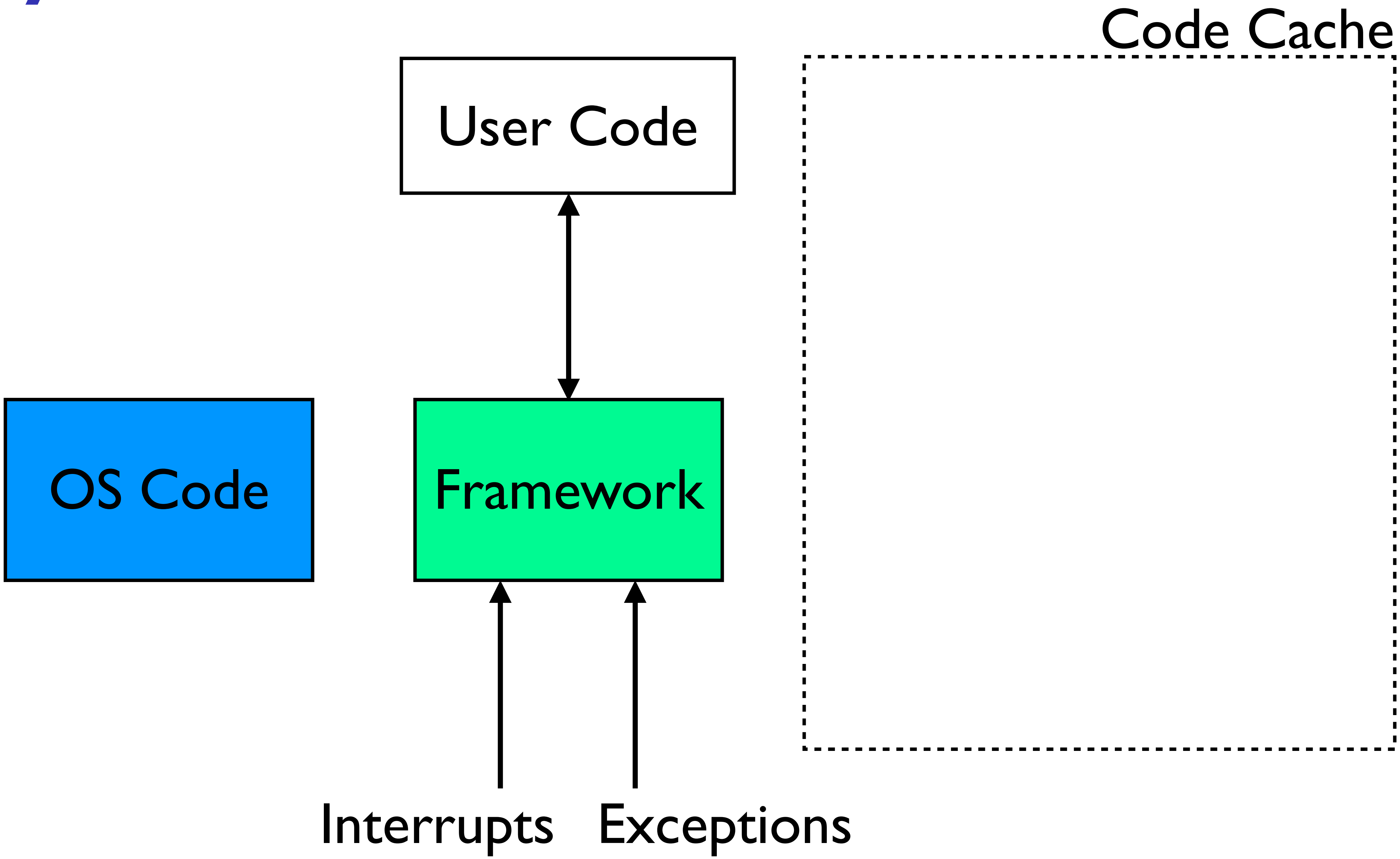

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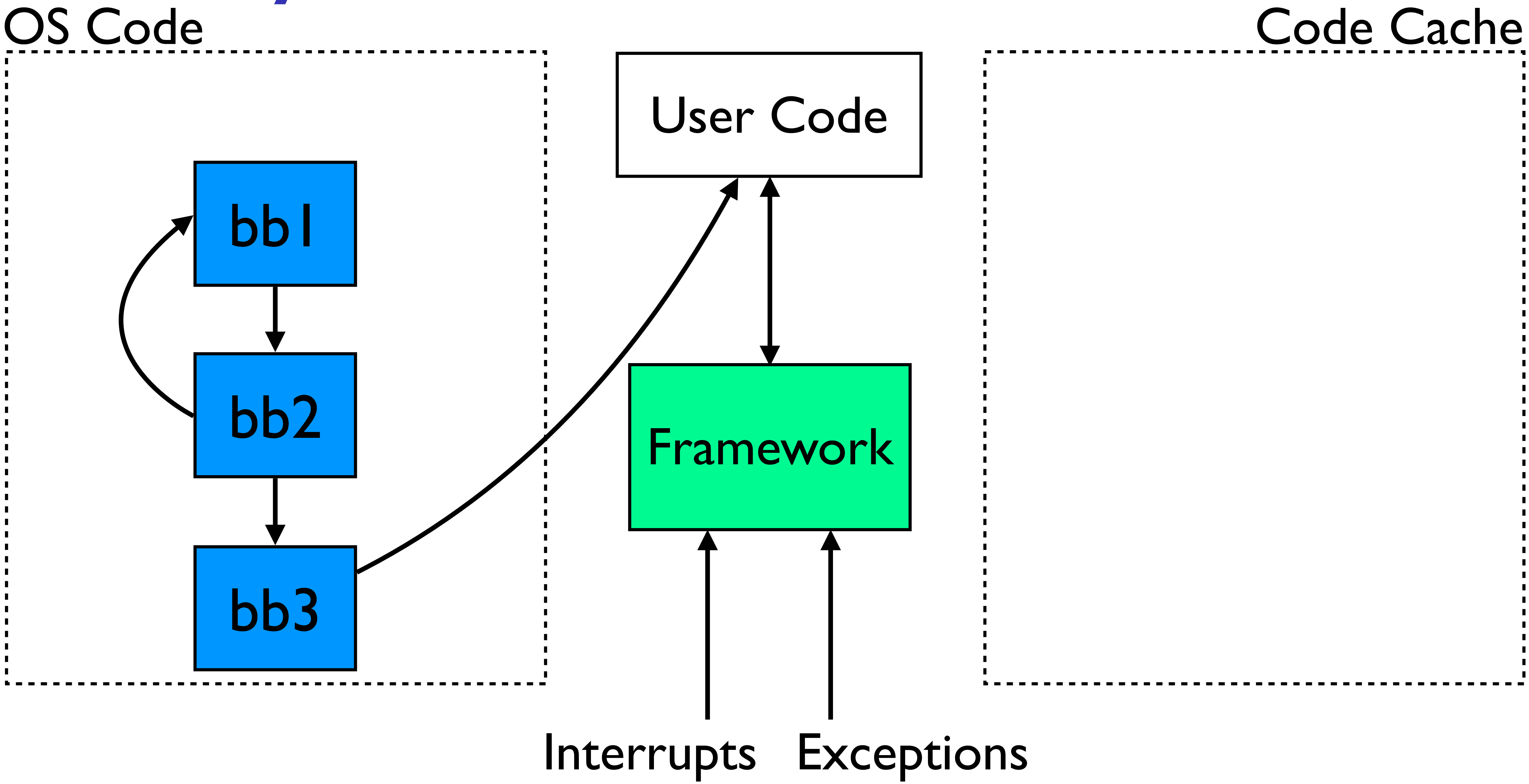

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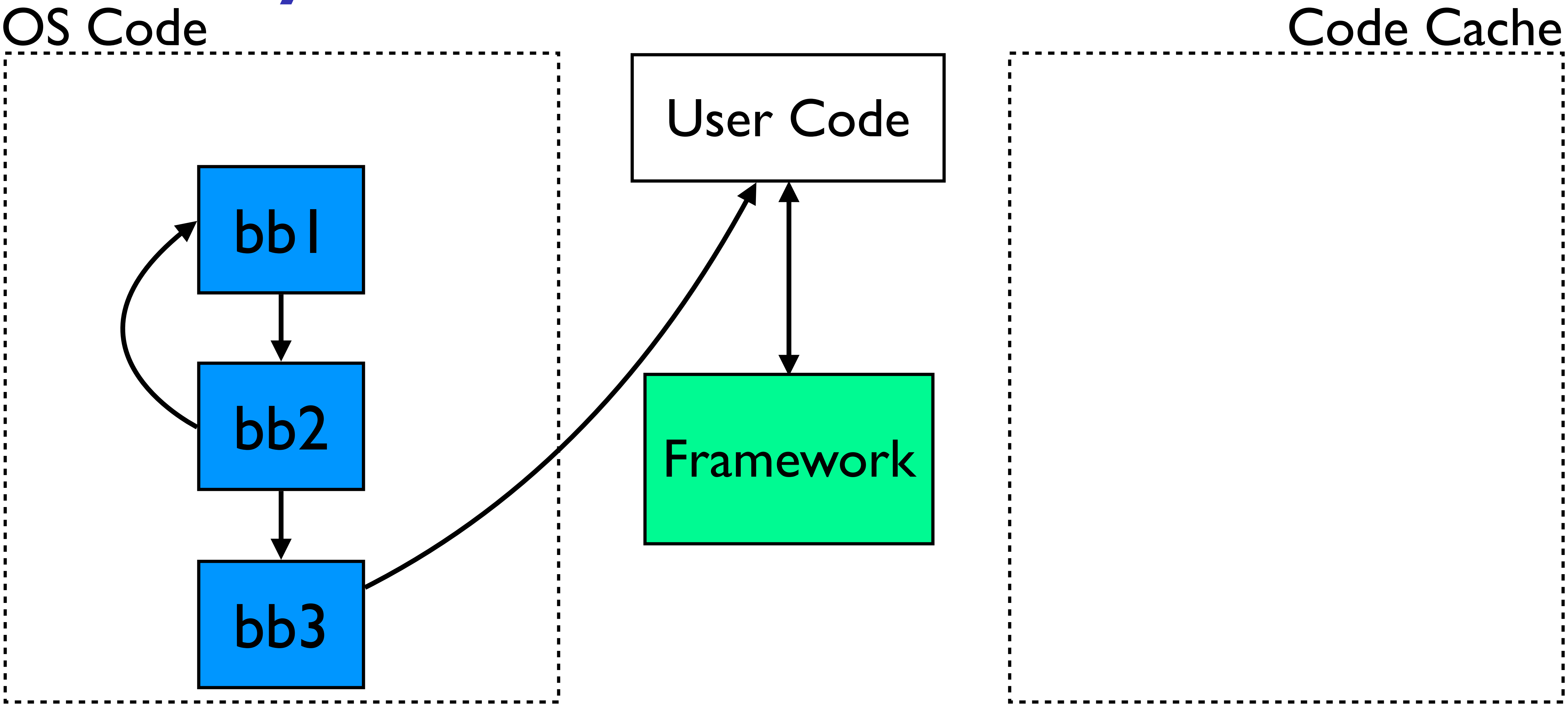

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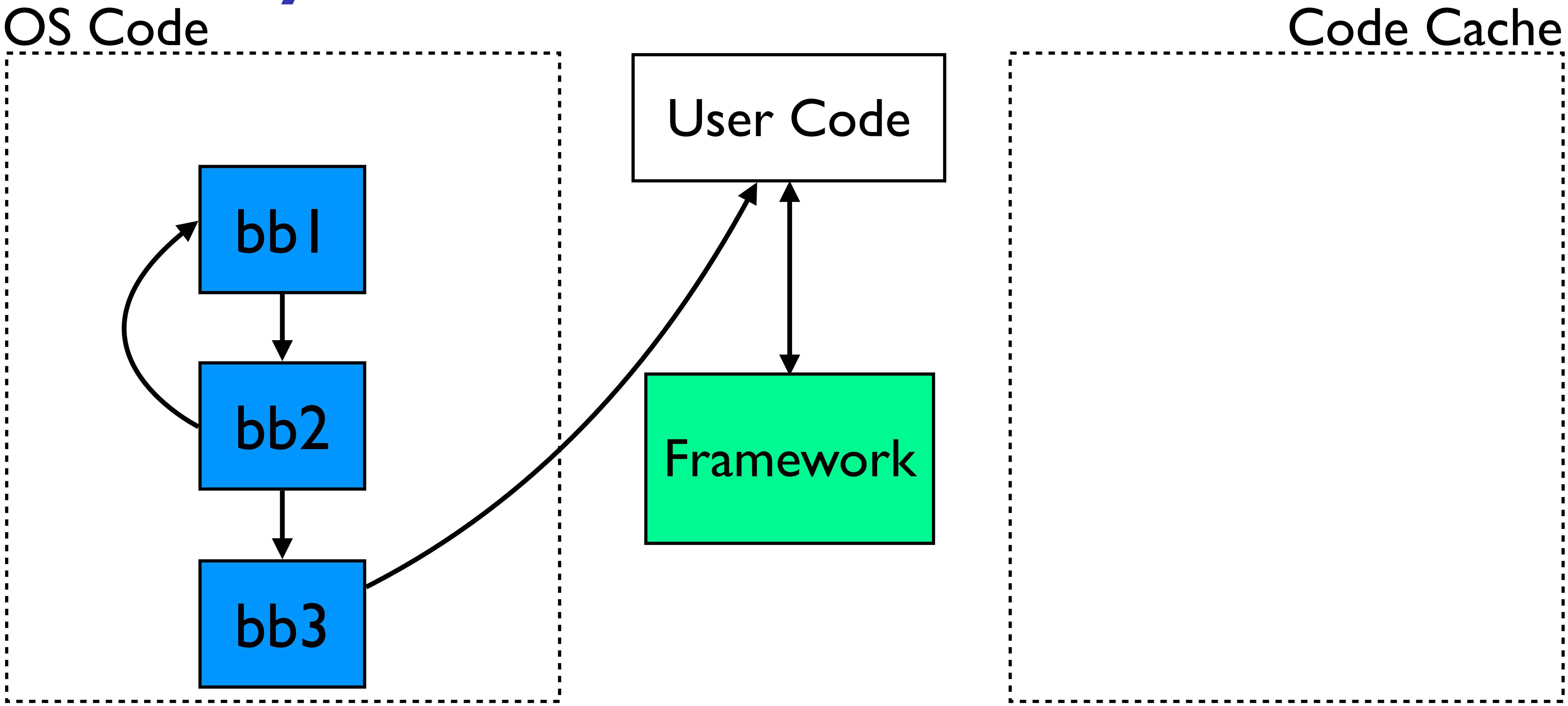

System call example

- bb1 is entry point

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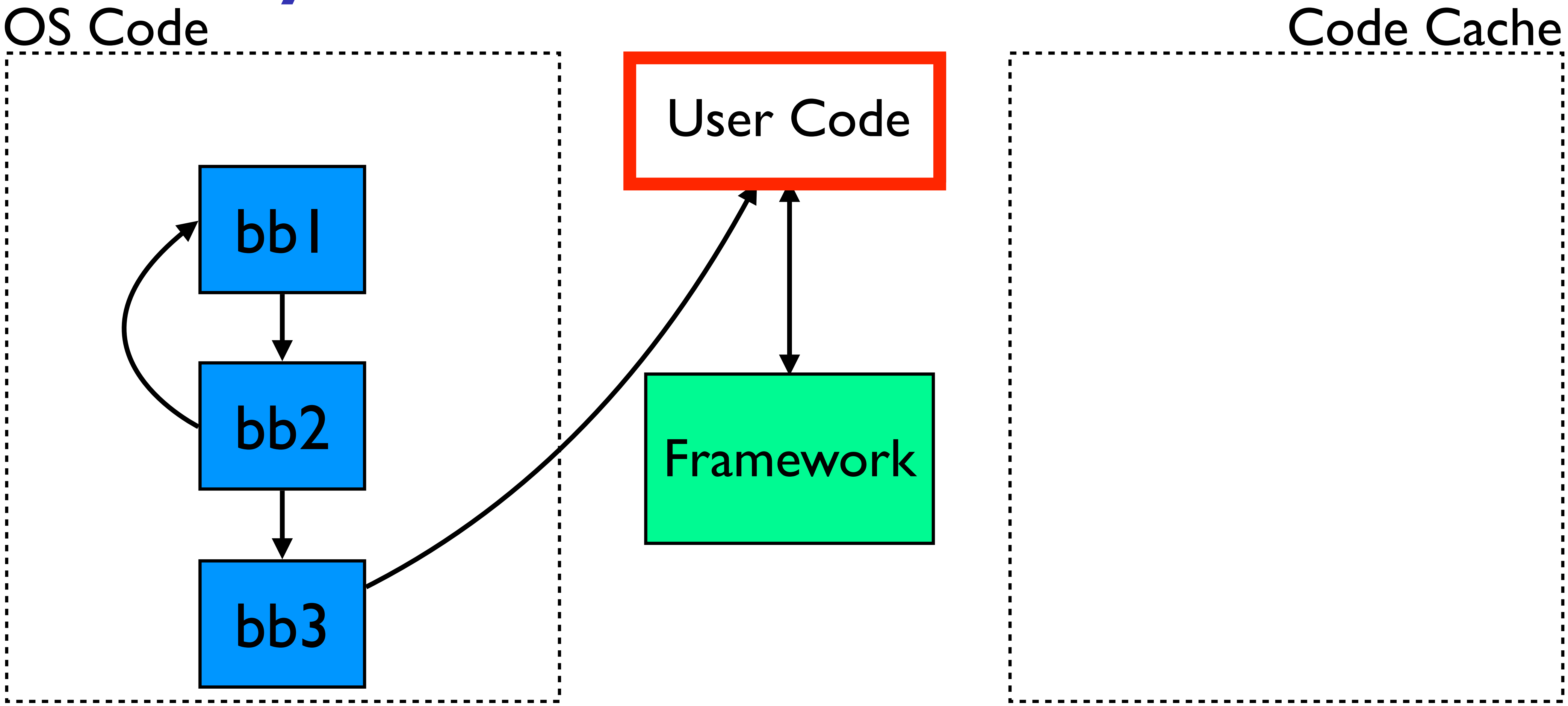

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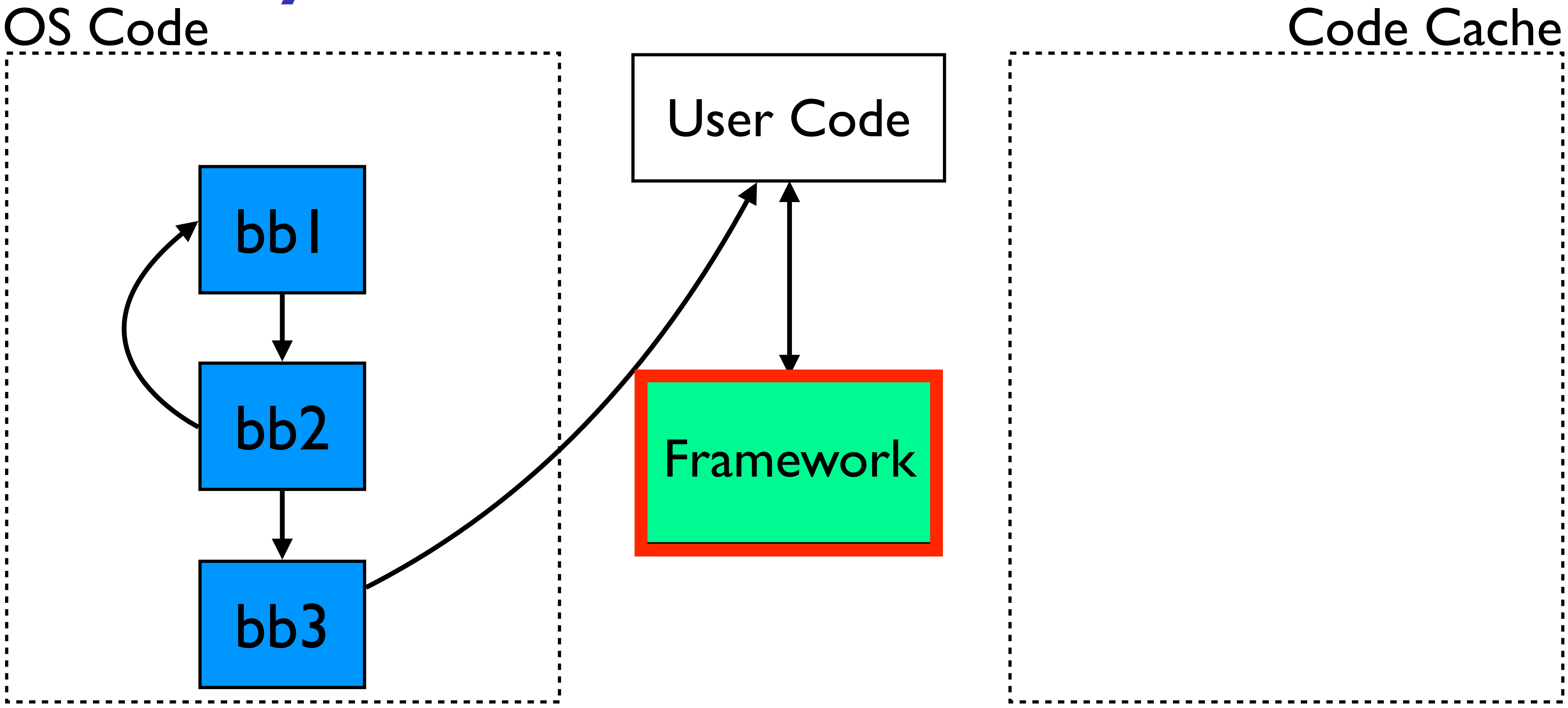

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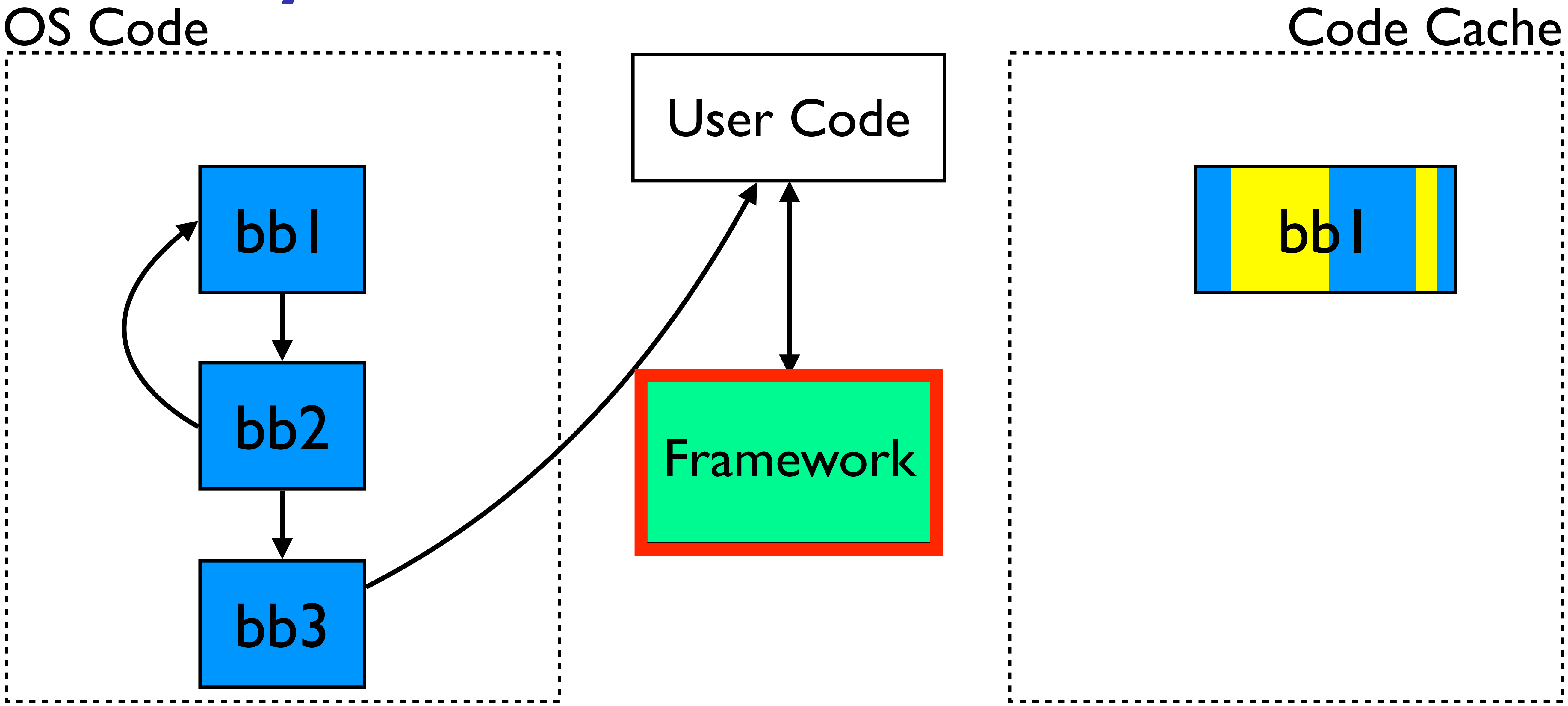

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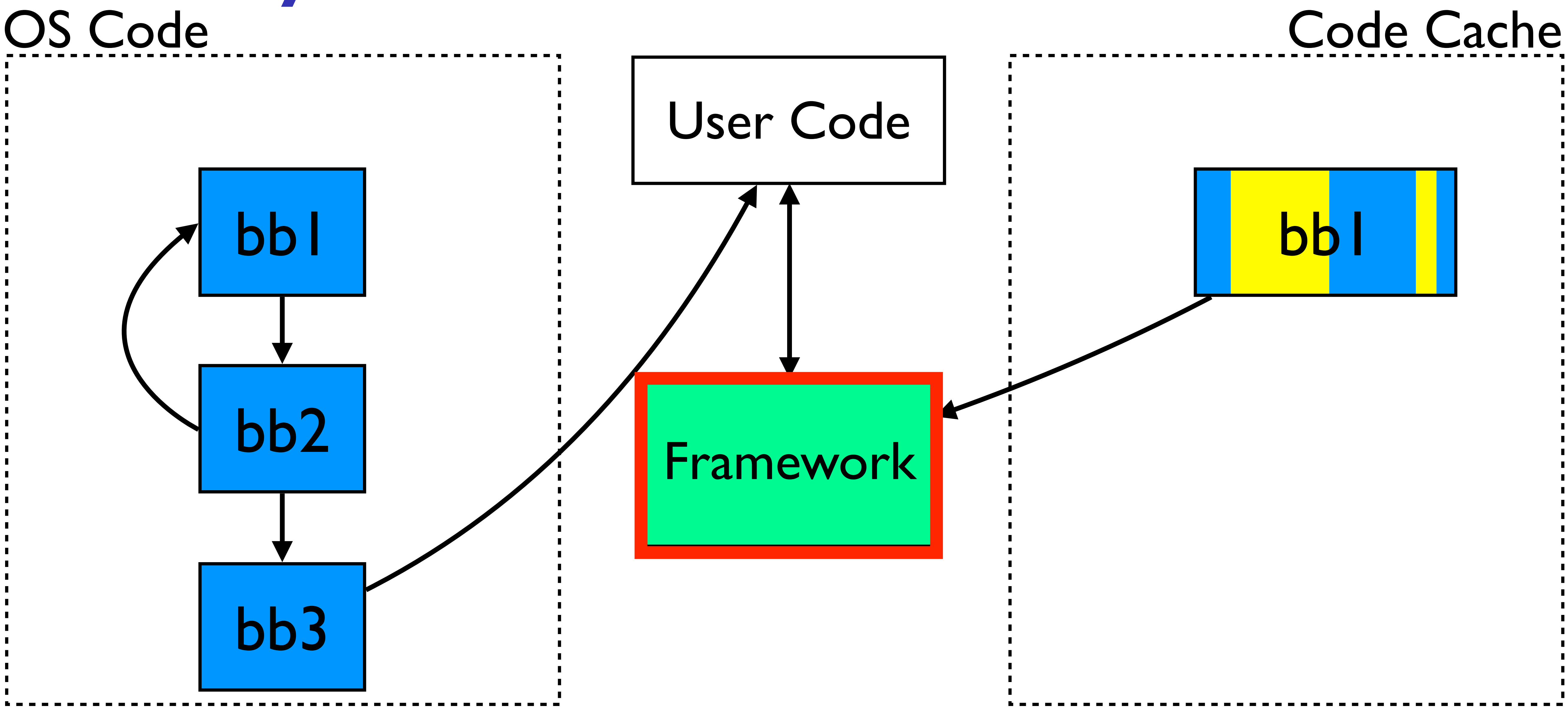

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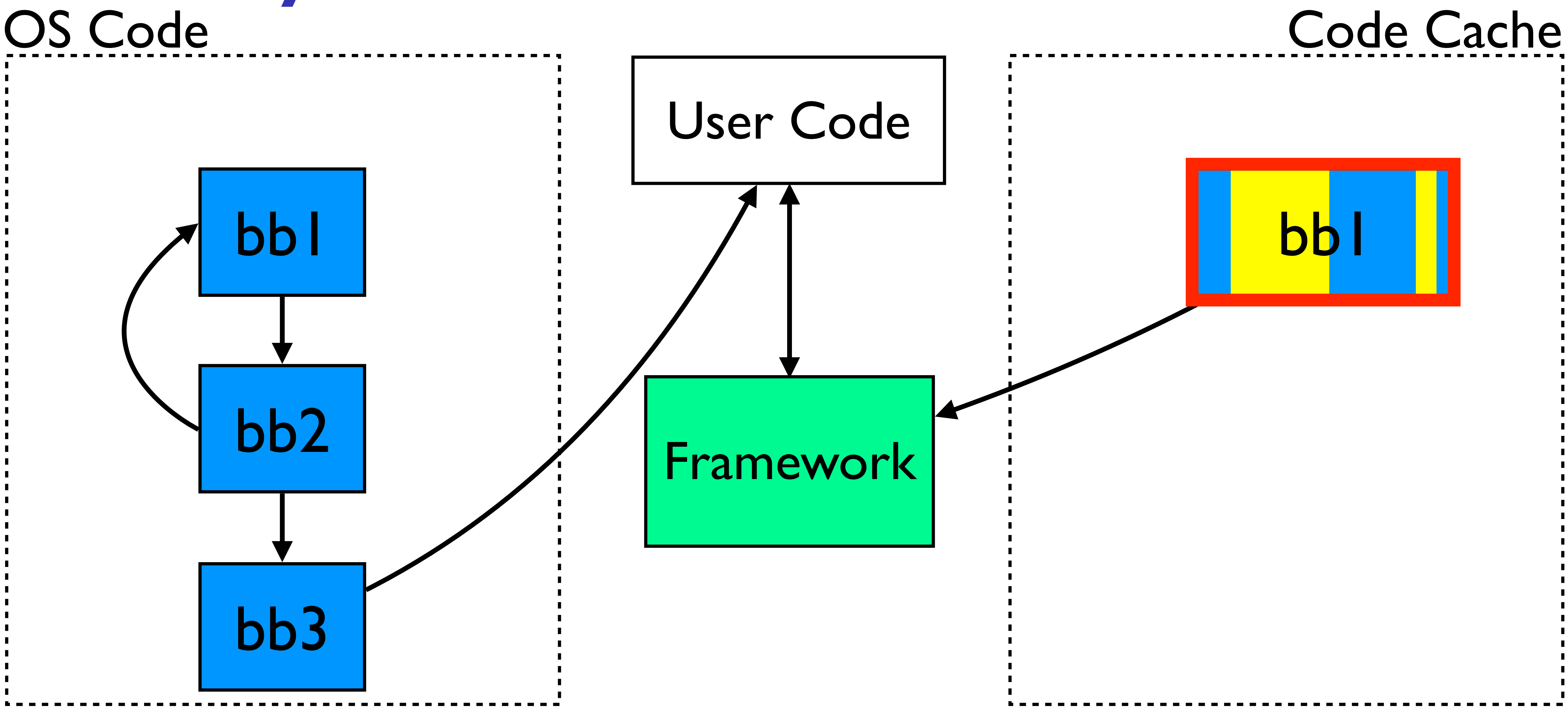

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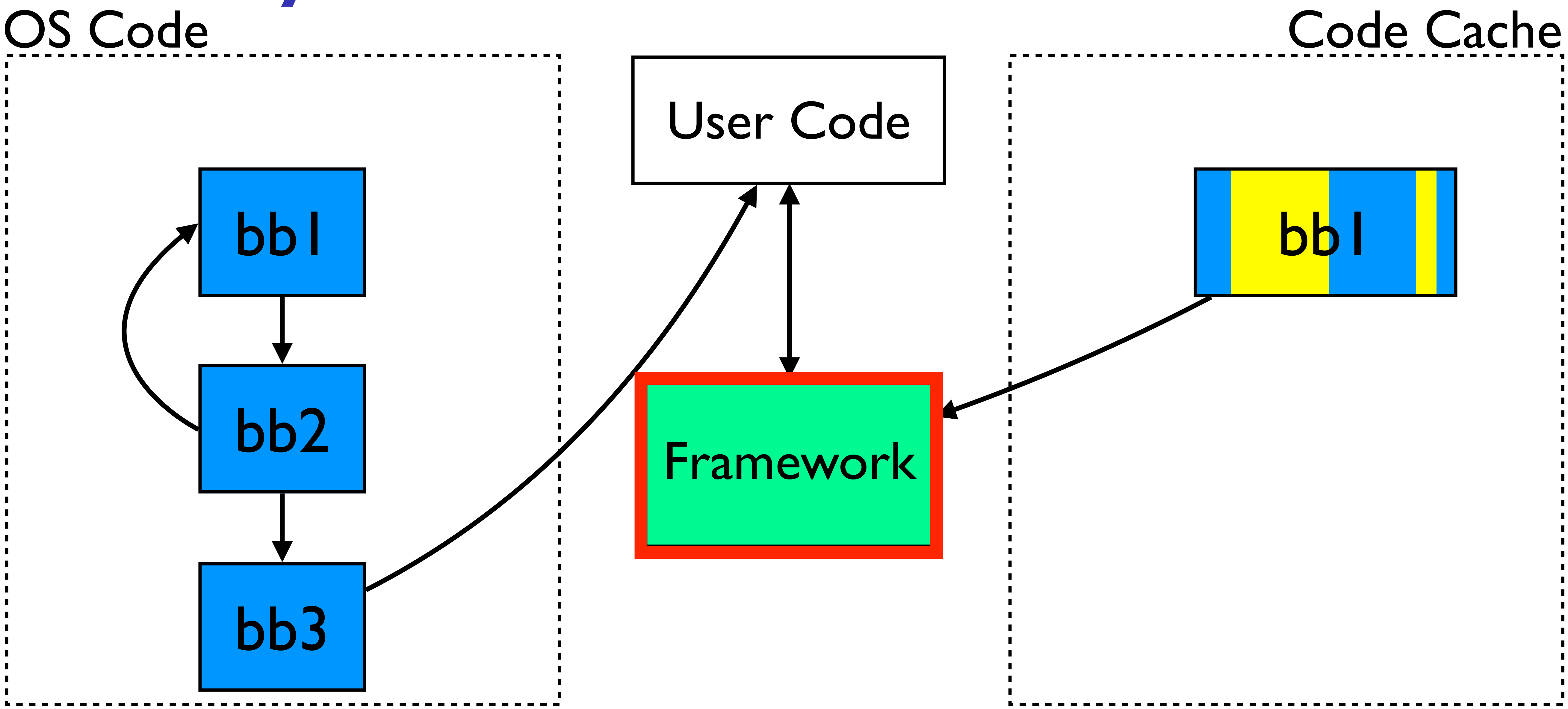

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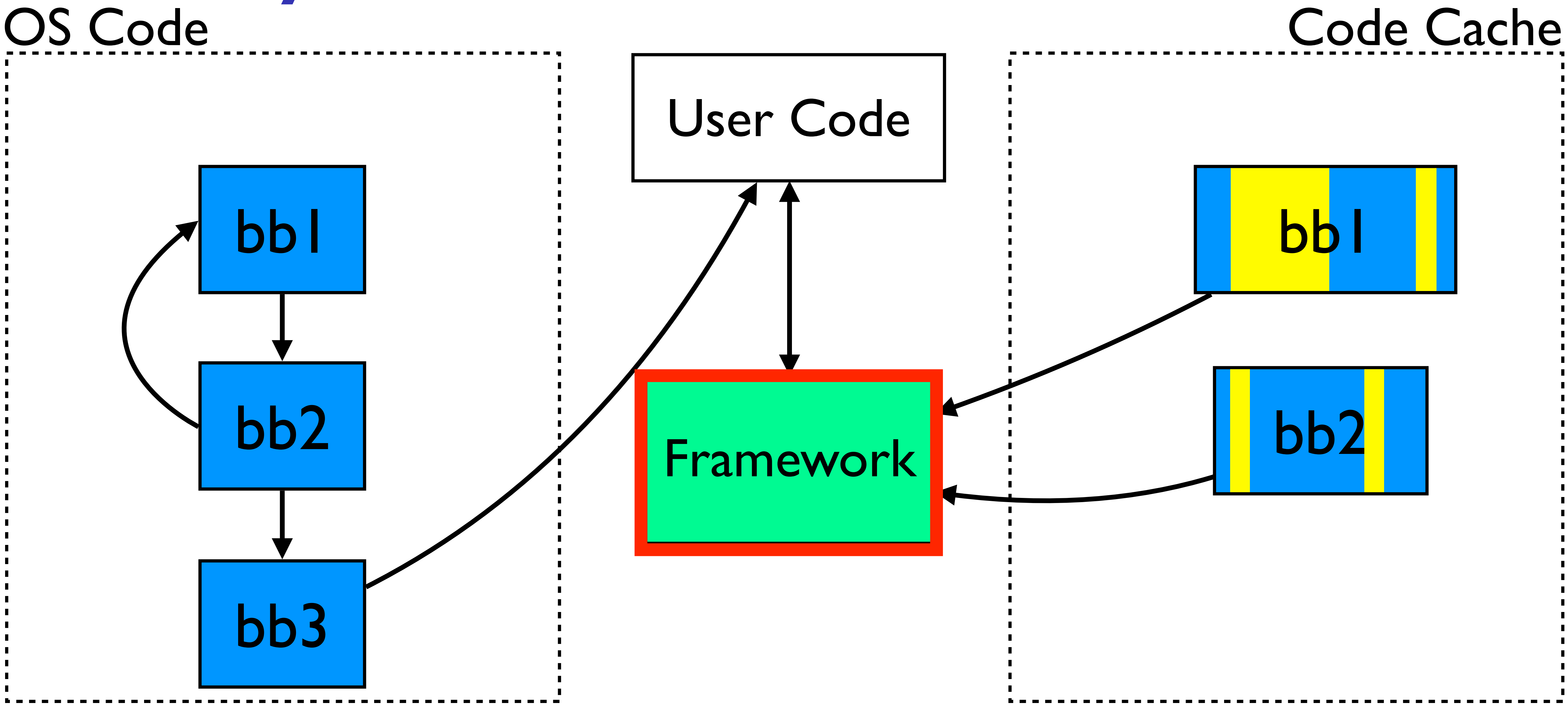

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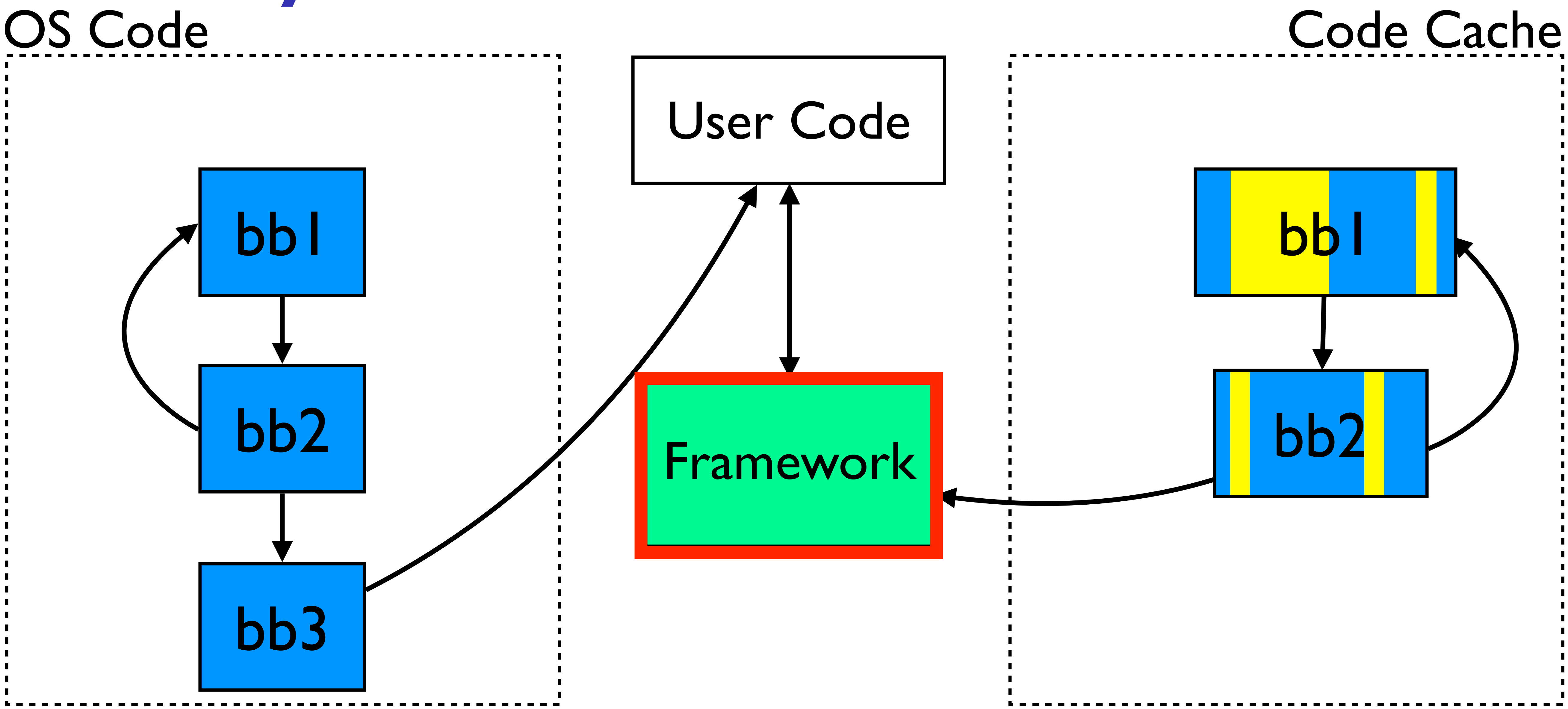

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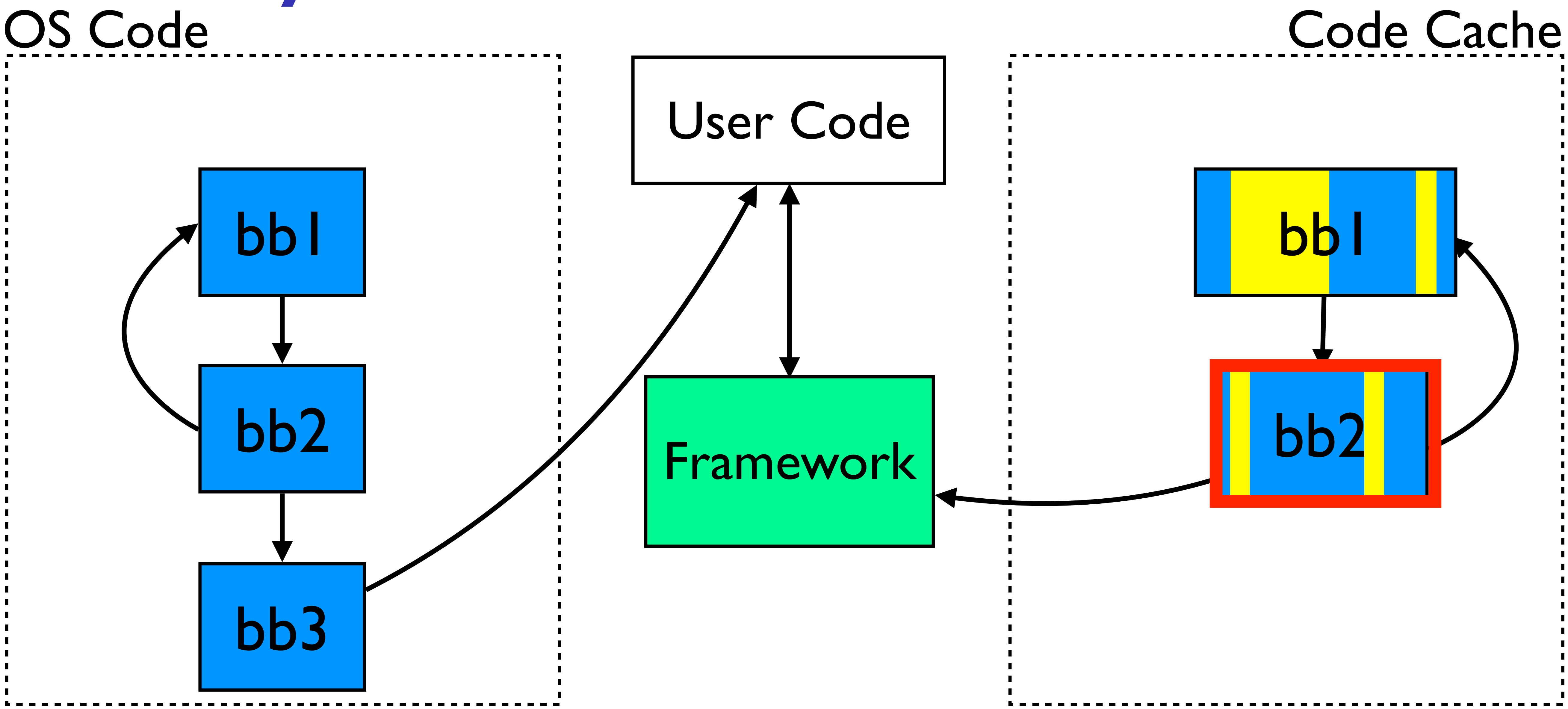

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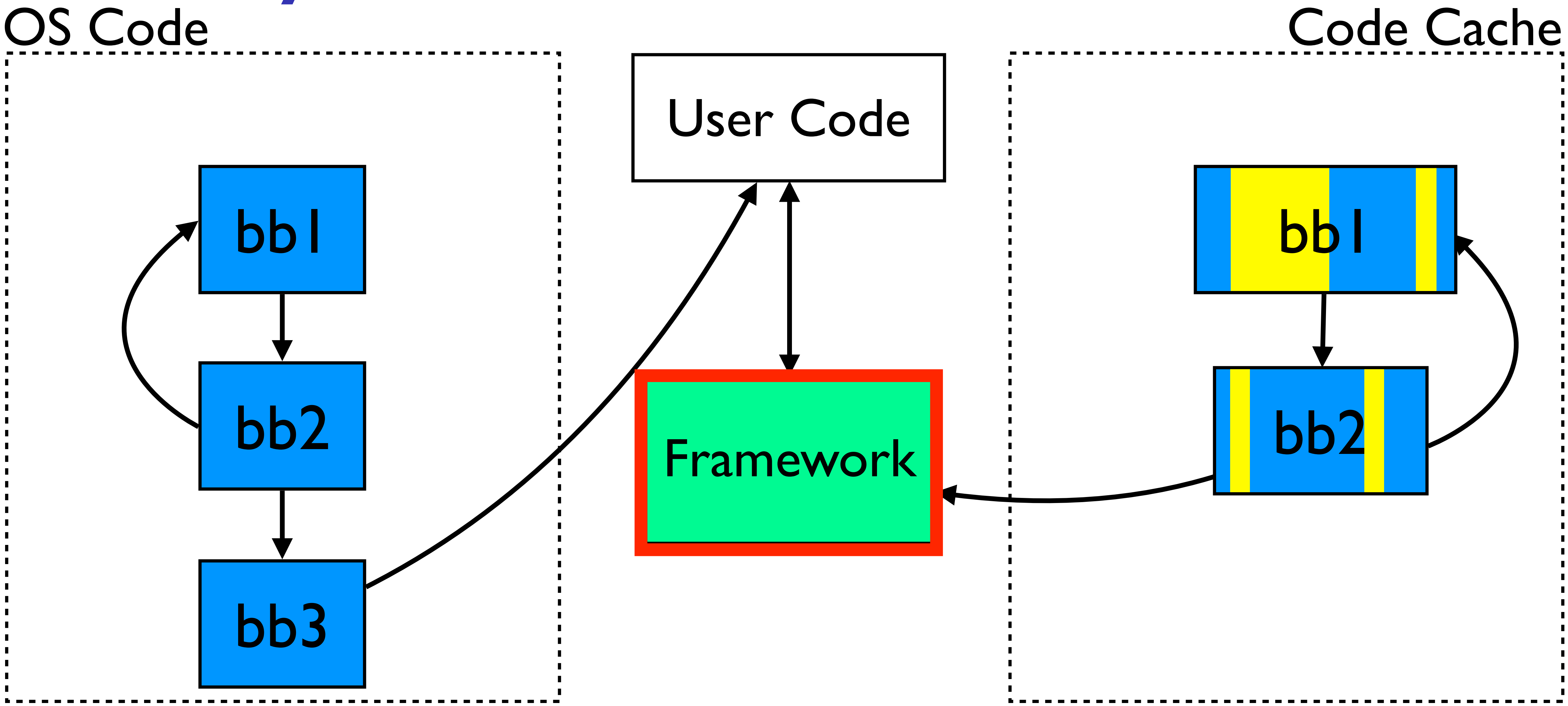

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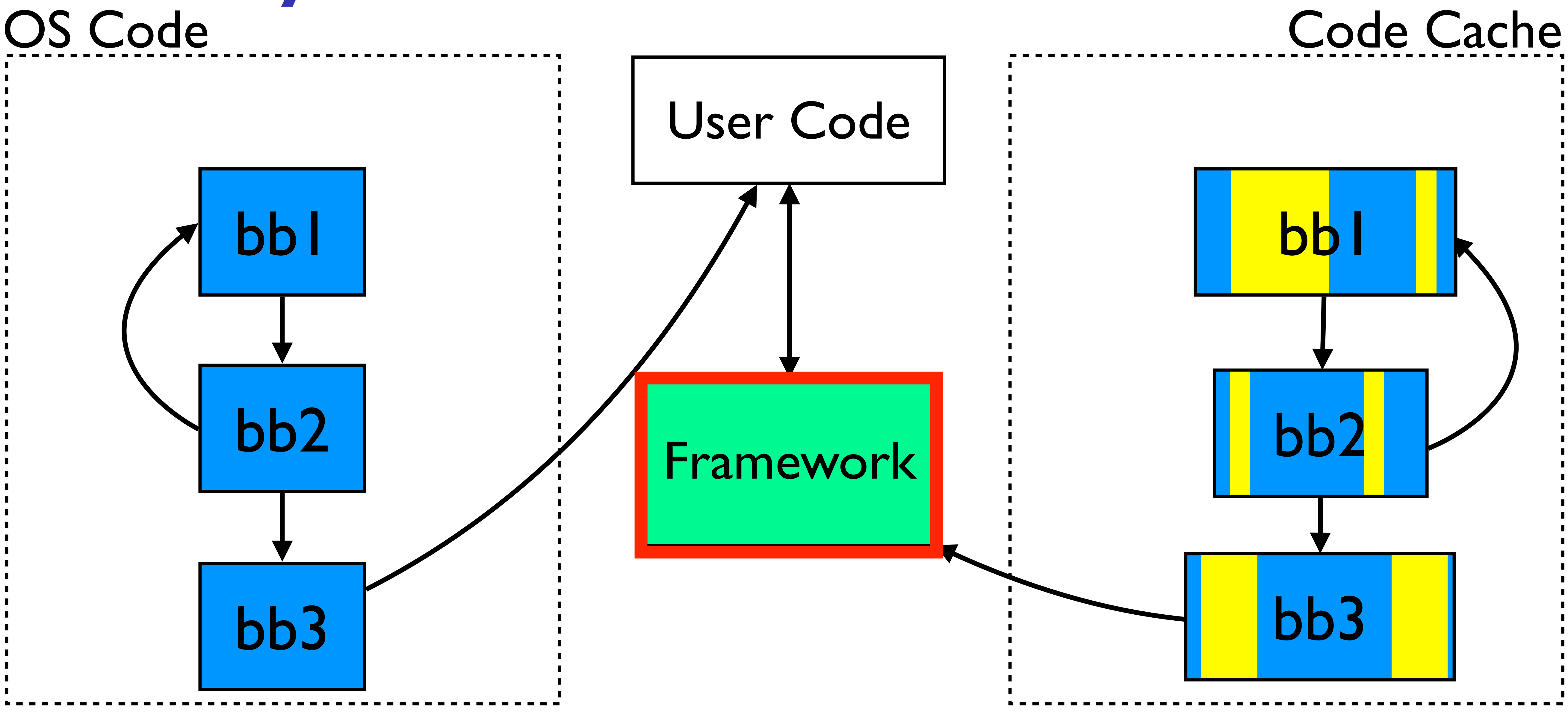

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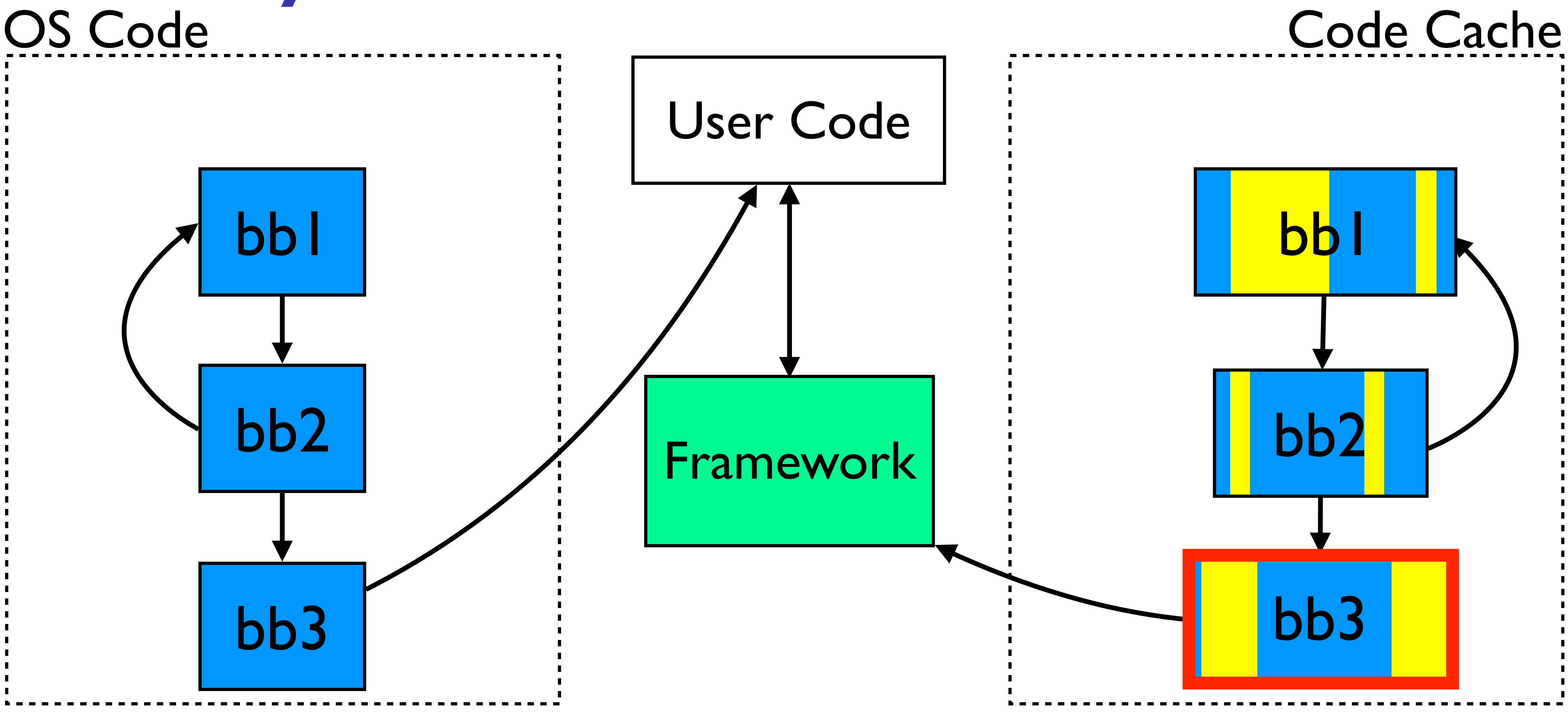

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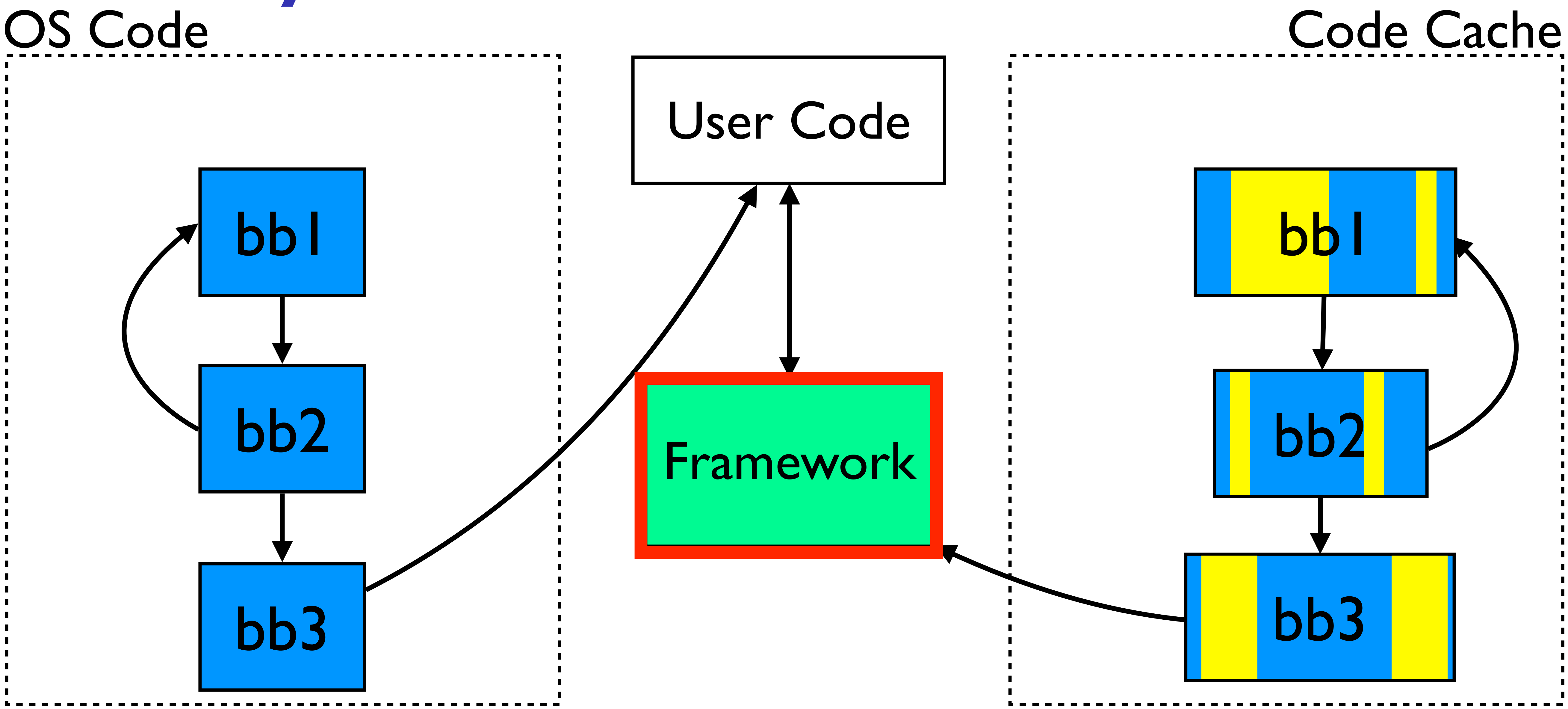

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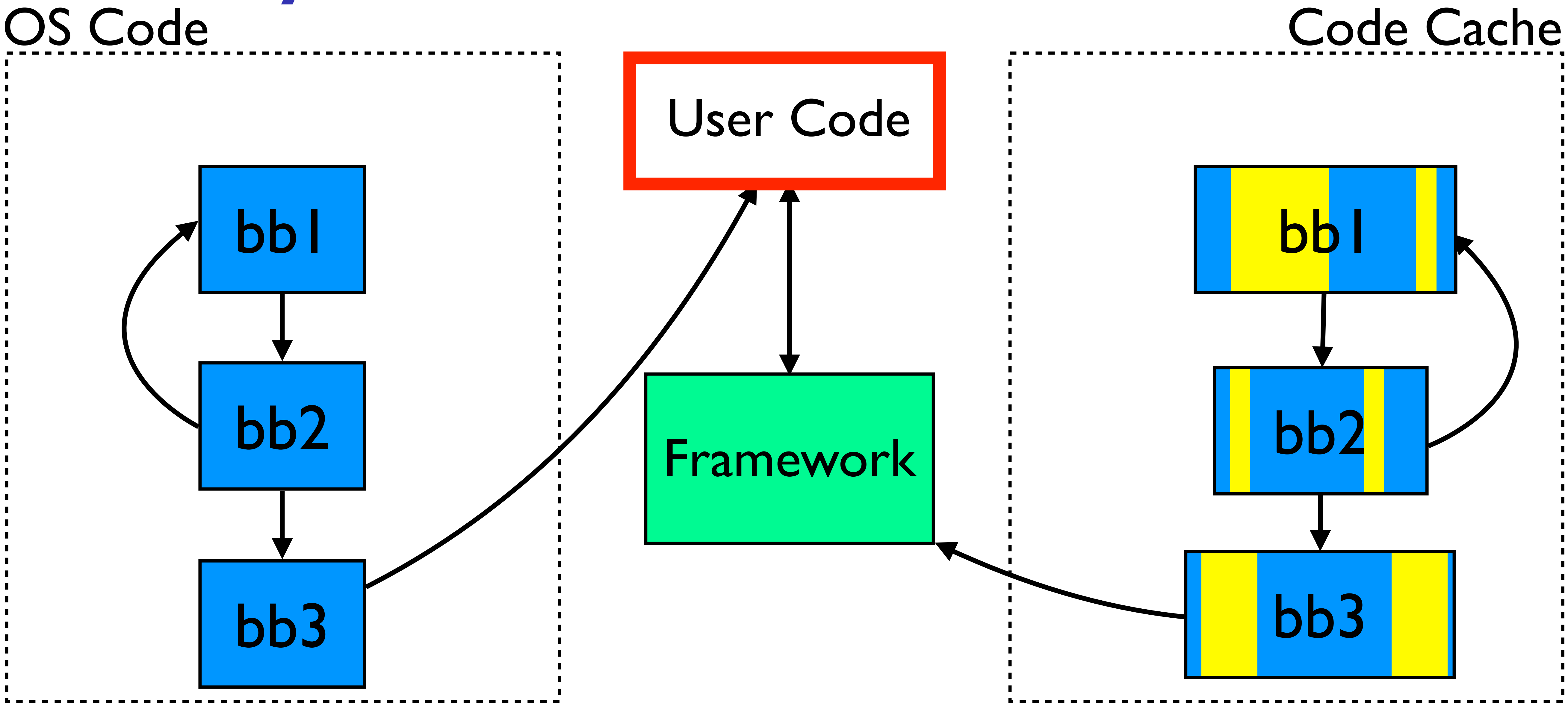

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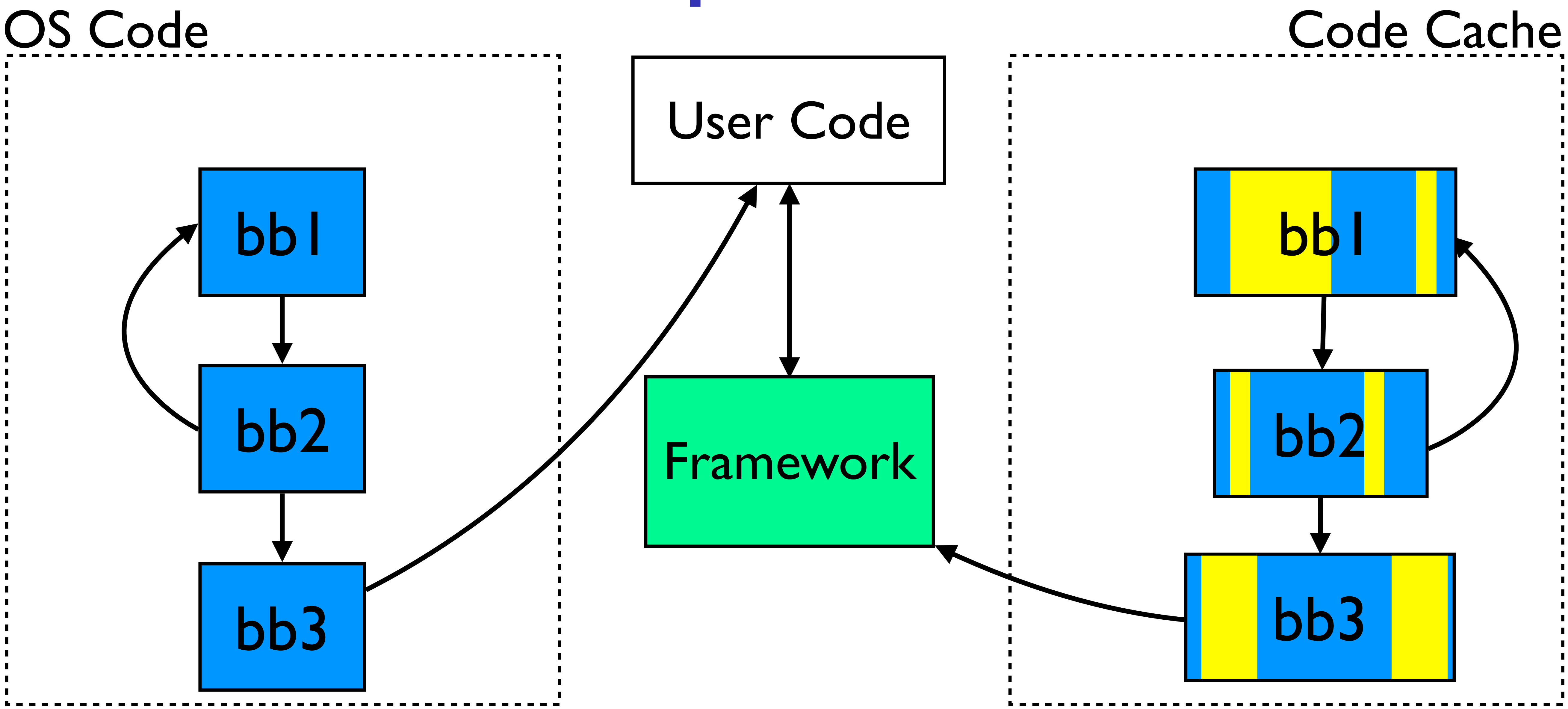

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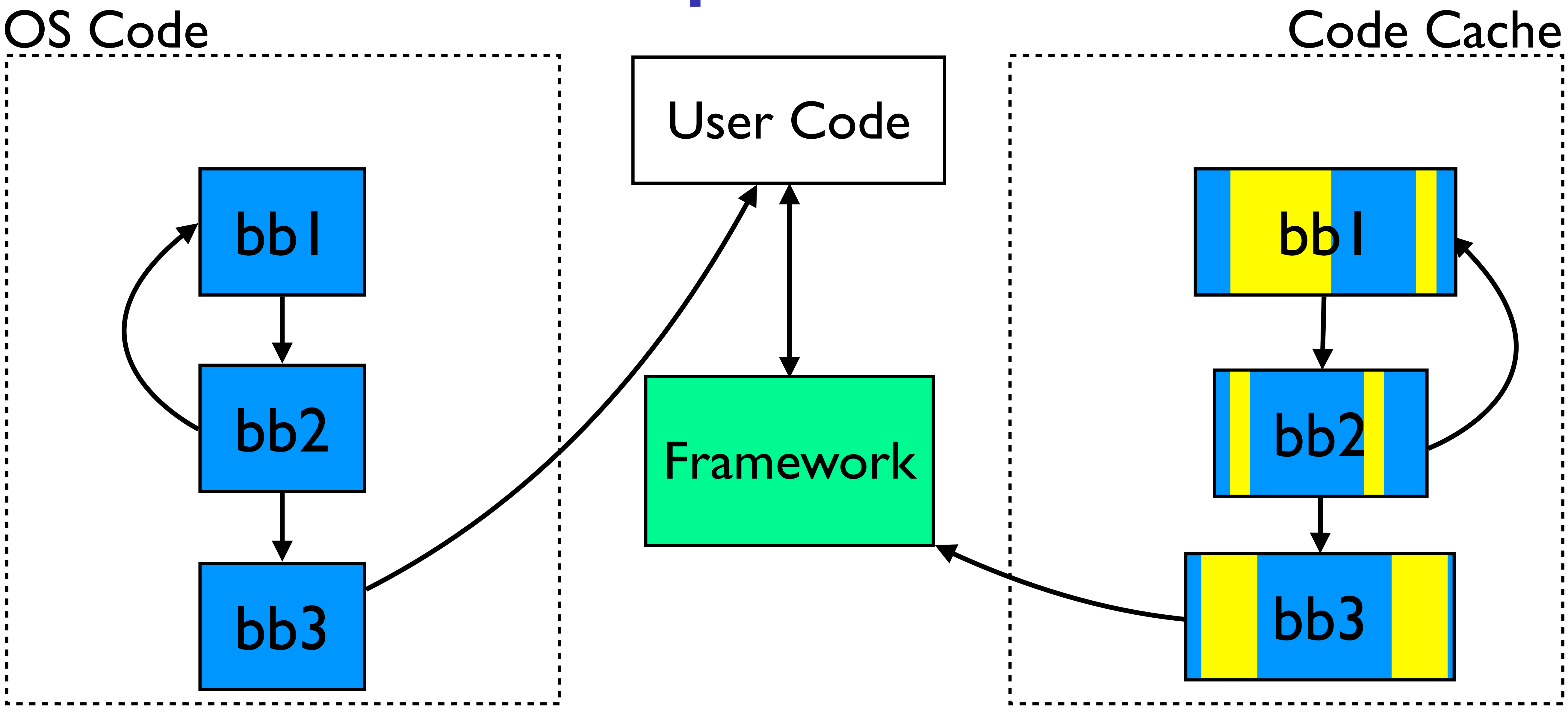

Reentrance

- How do you do I/O?
- Can't use OS

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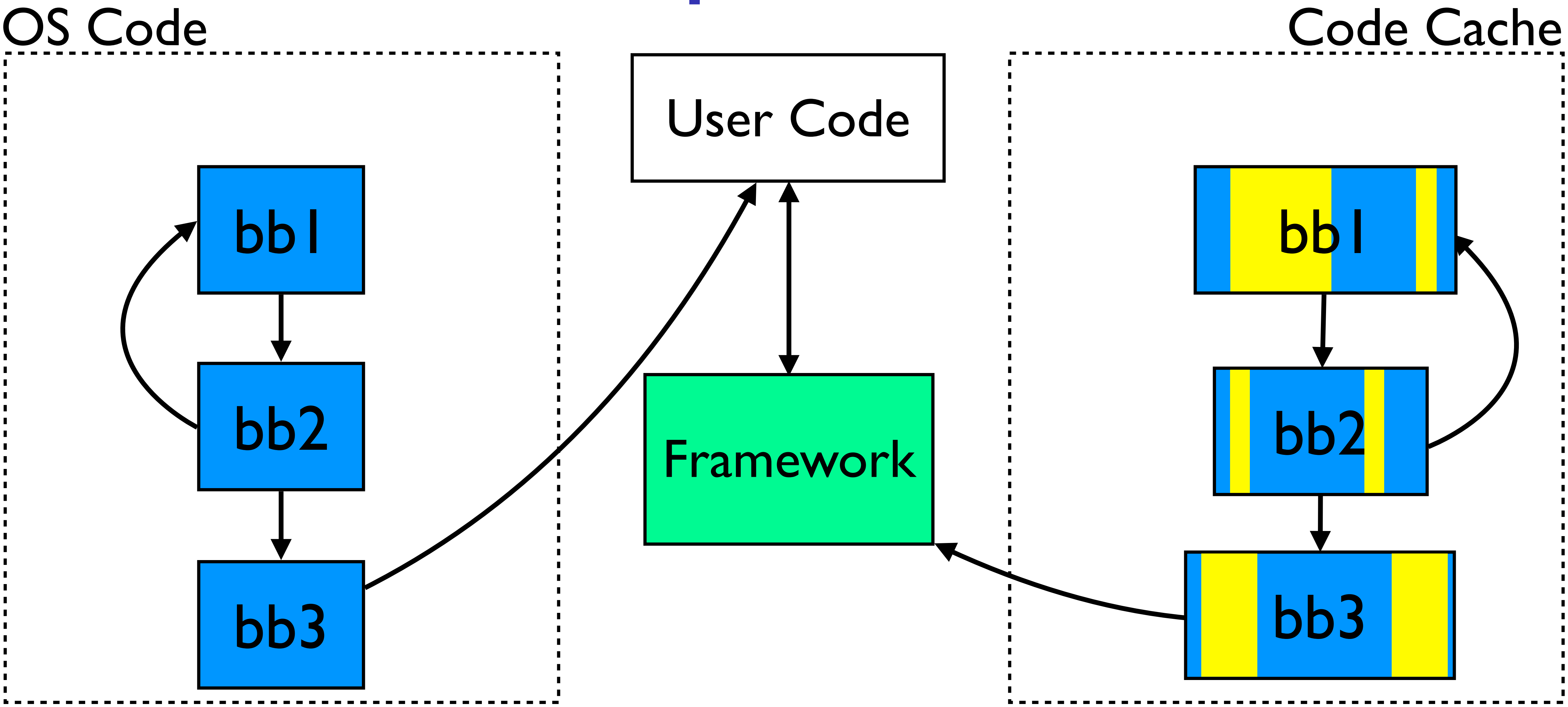

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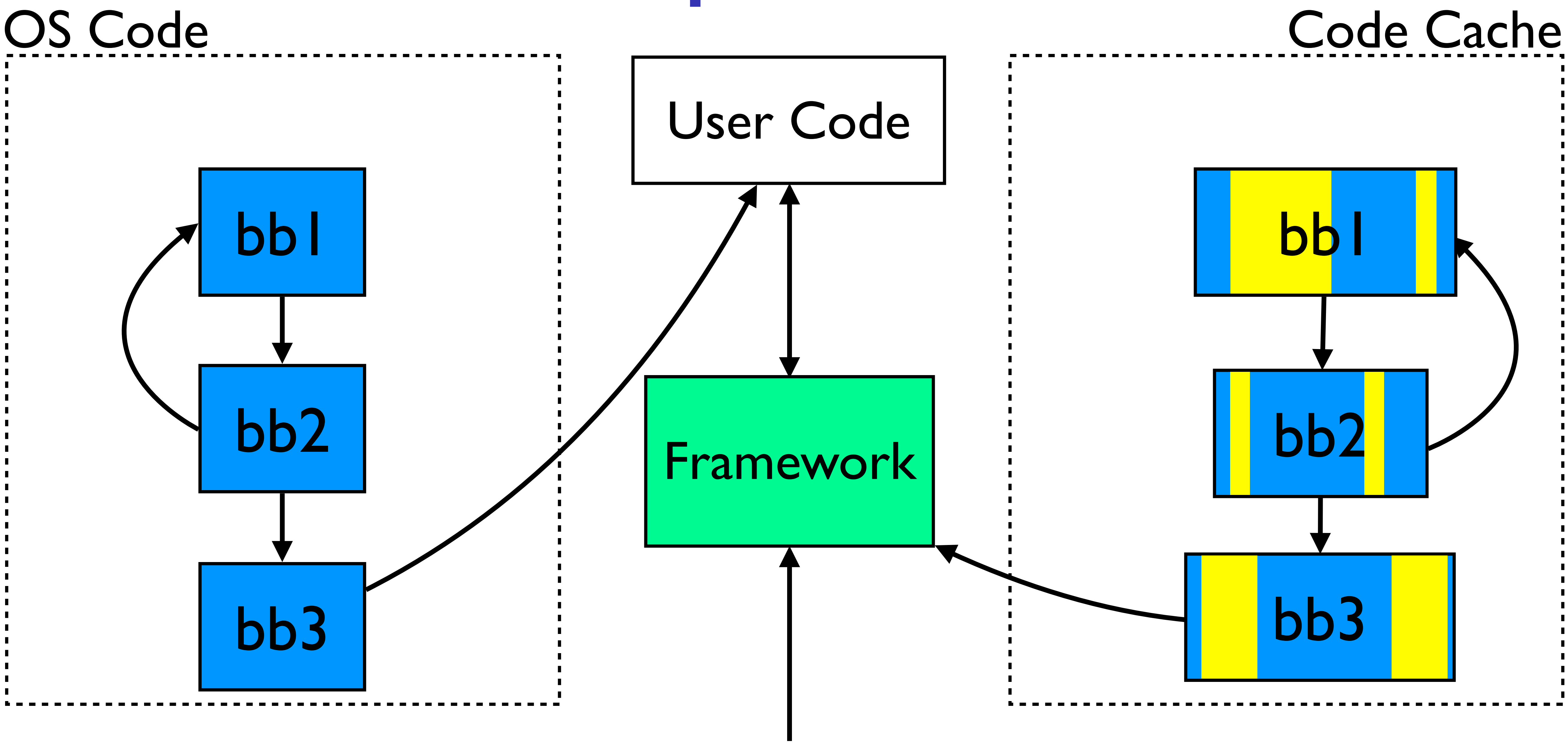

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Interrupts

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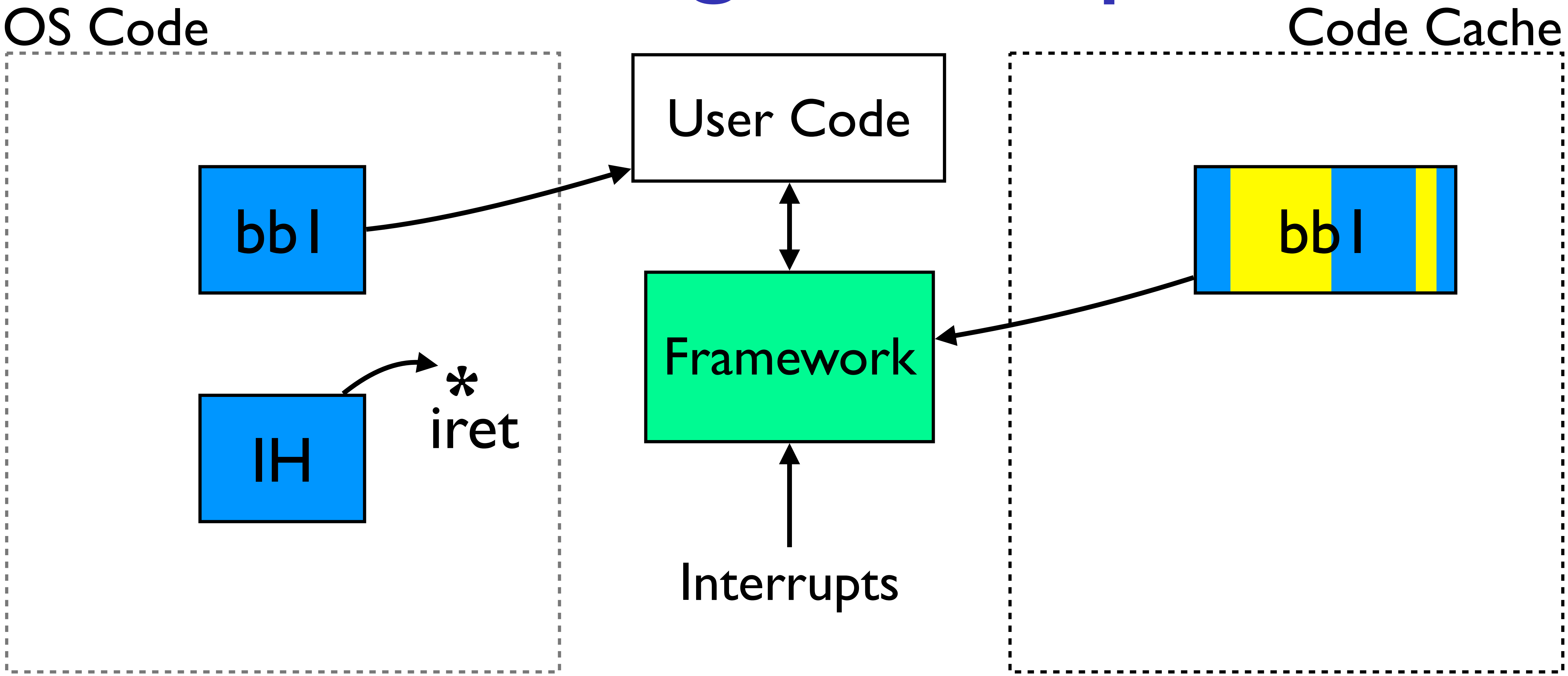

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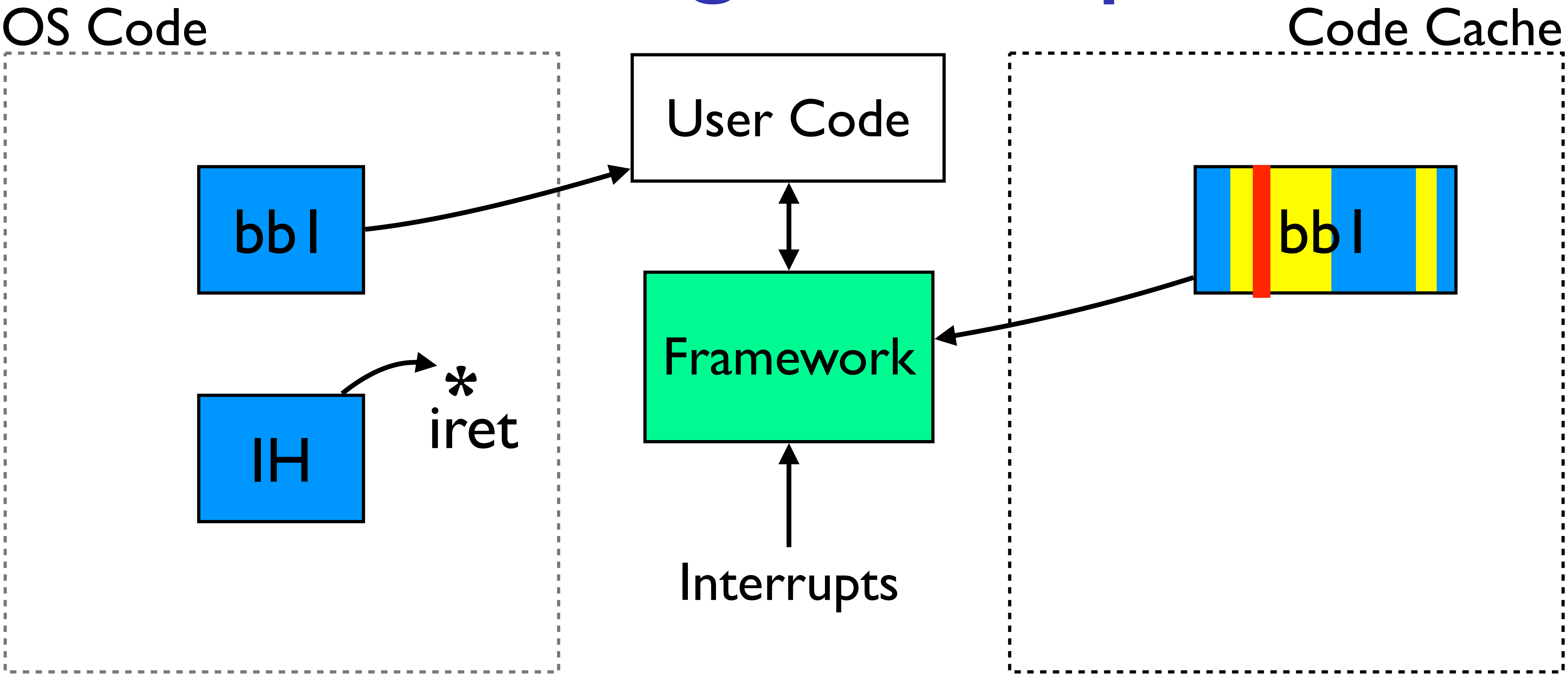

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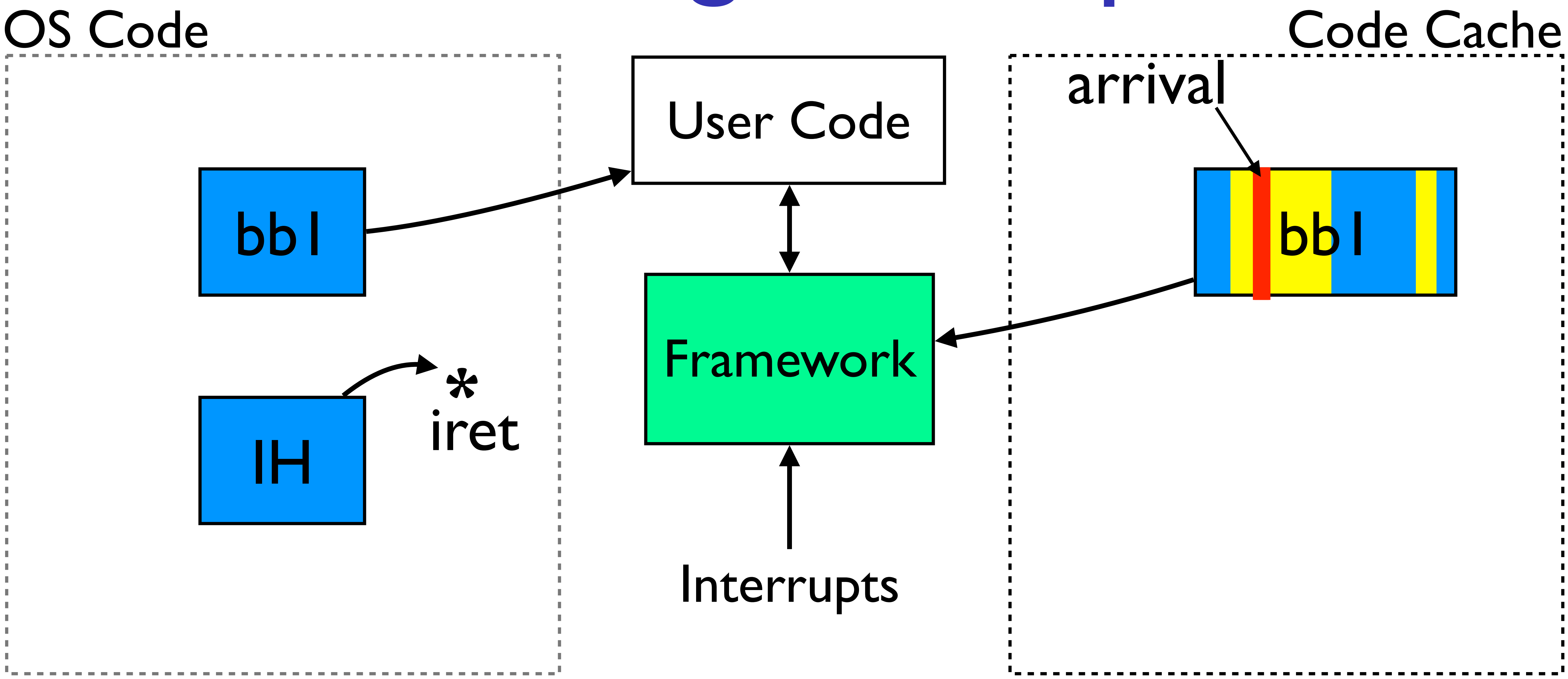

OS Code

bb1

IH

*

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User Code

Framework

Interrupts

Code Cache

arrival

bb1

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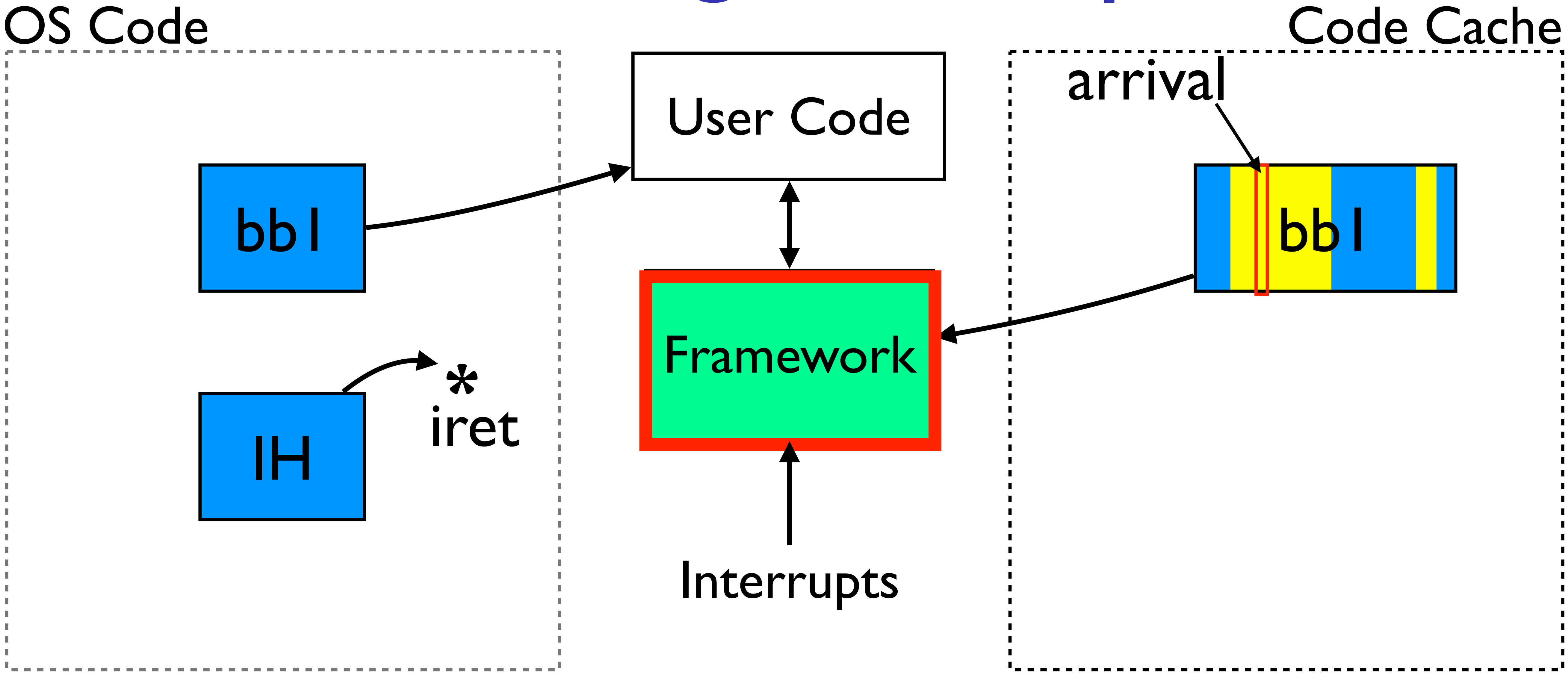

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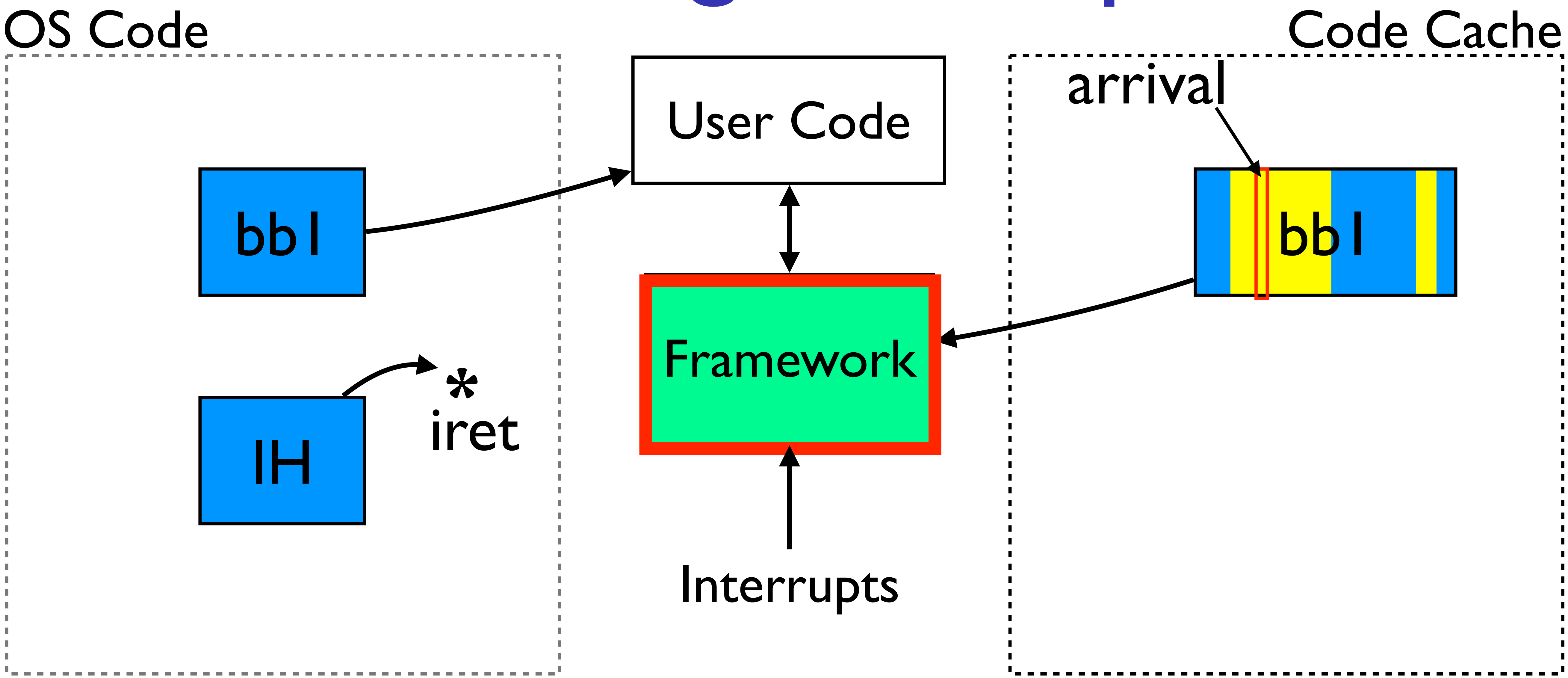

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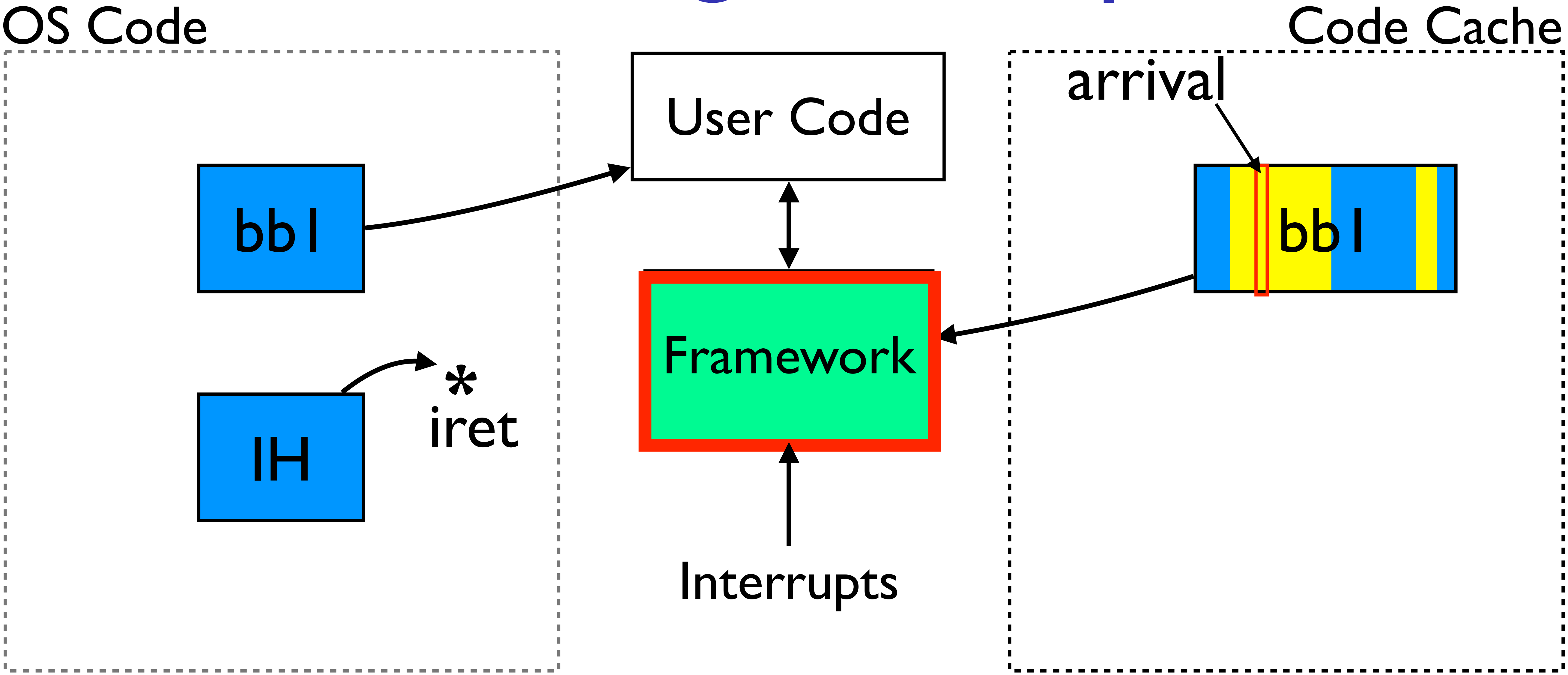

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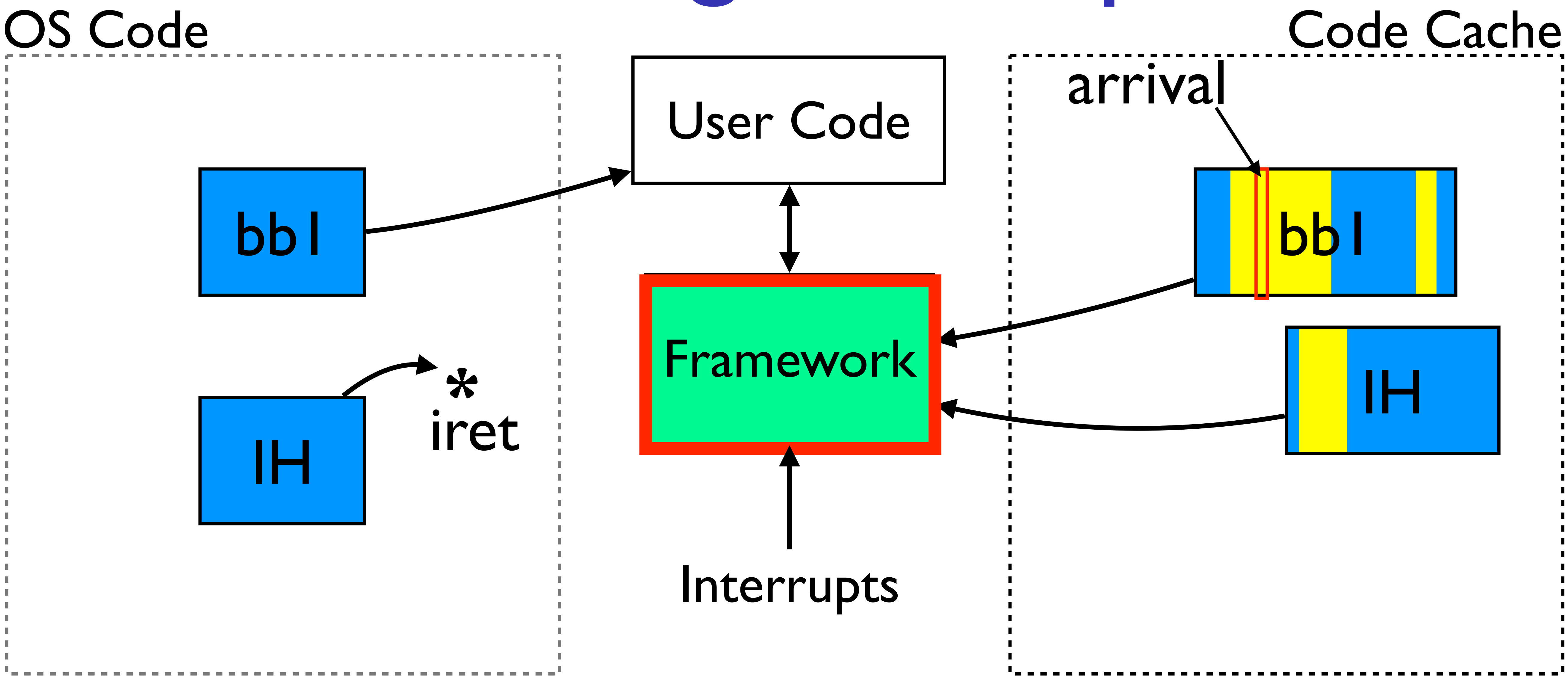

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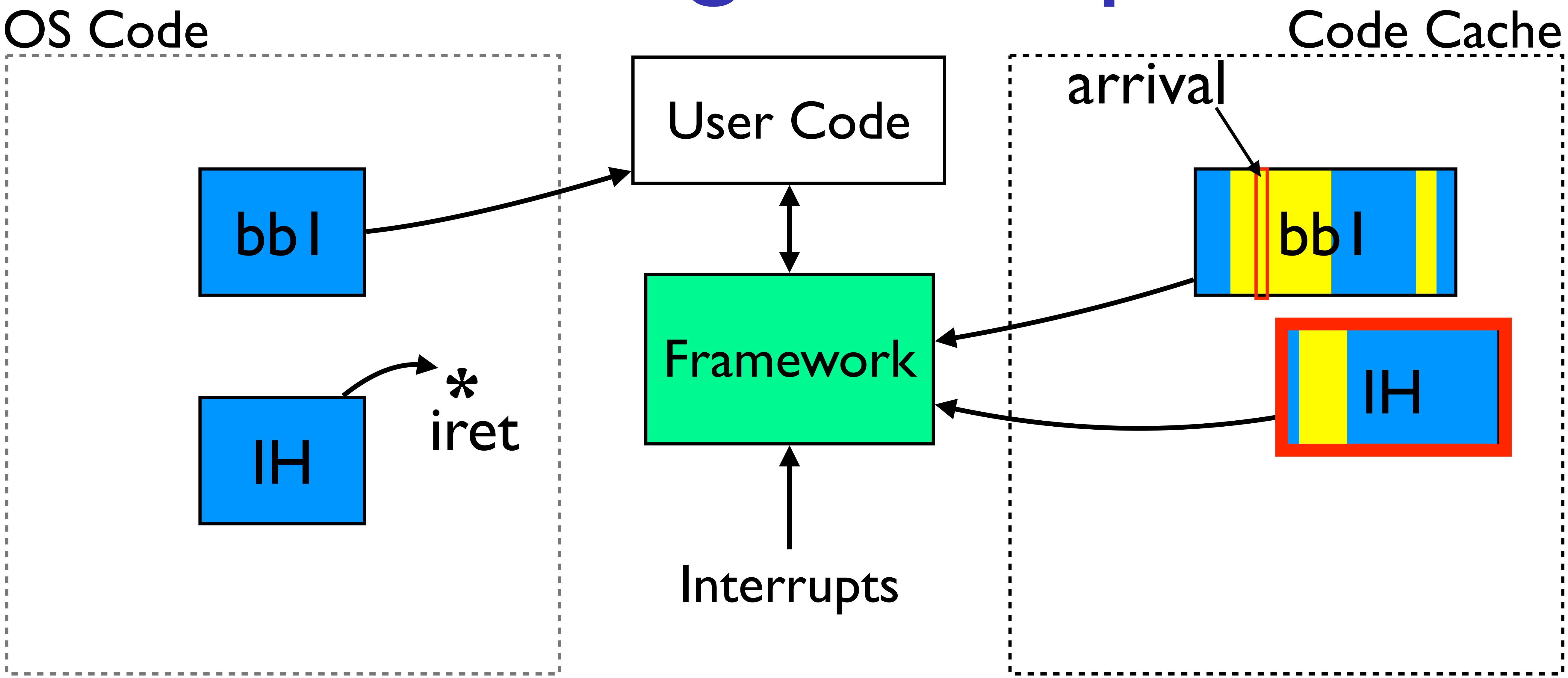

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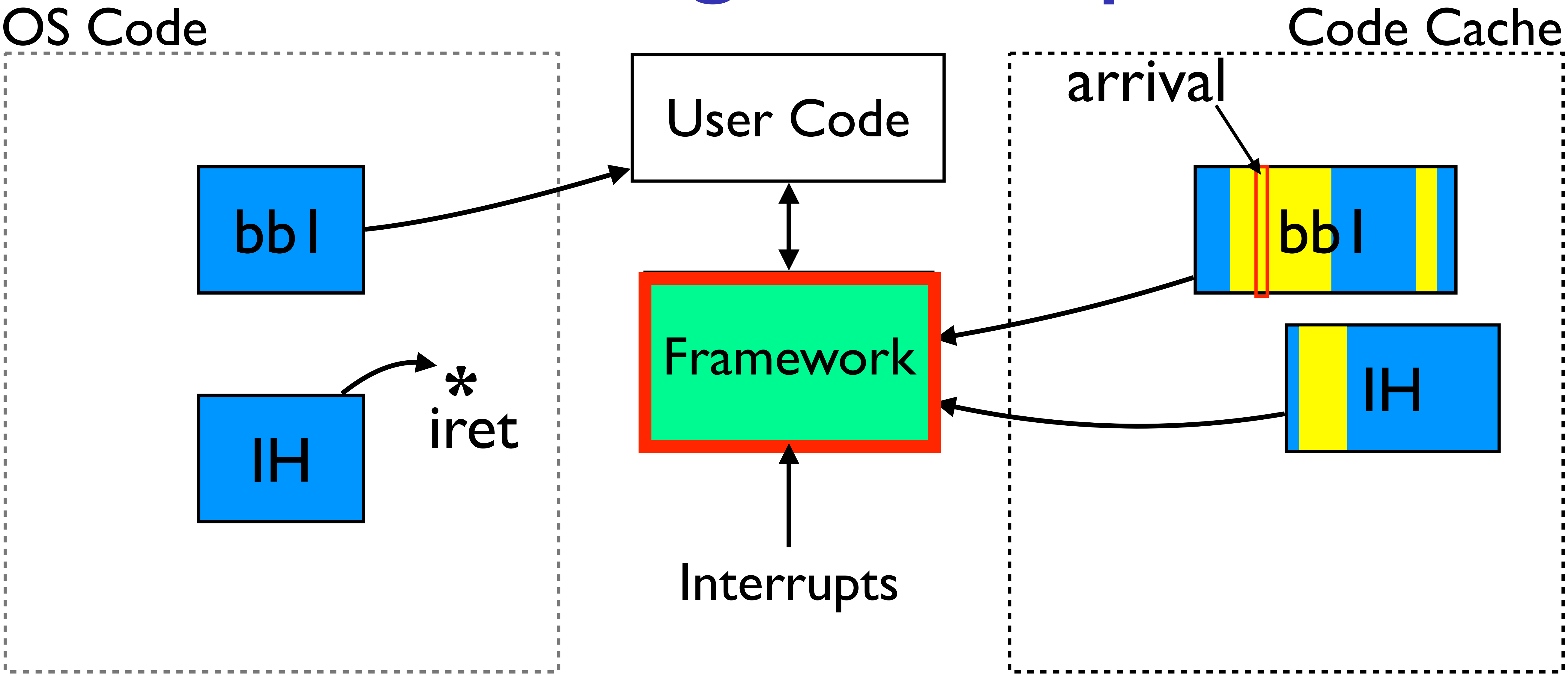

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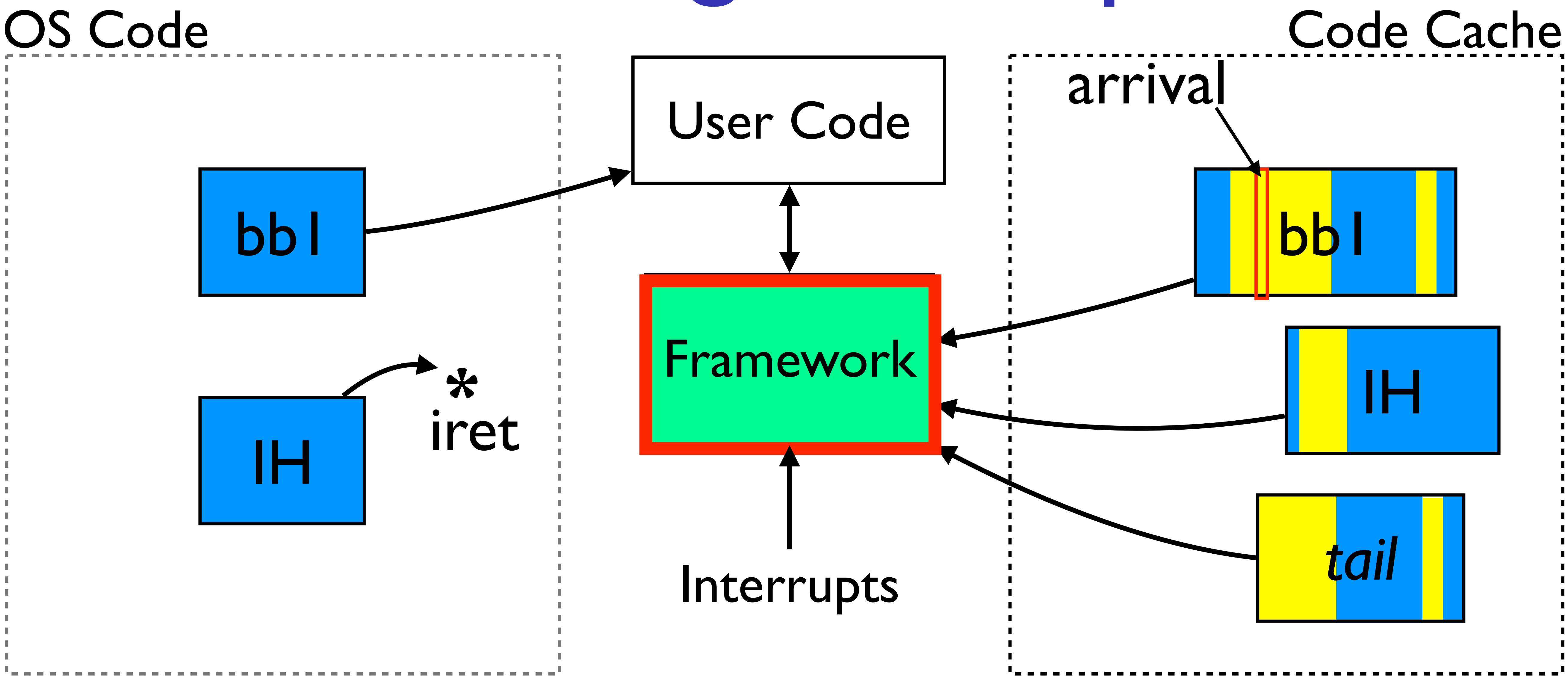

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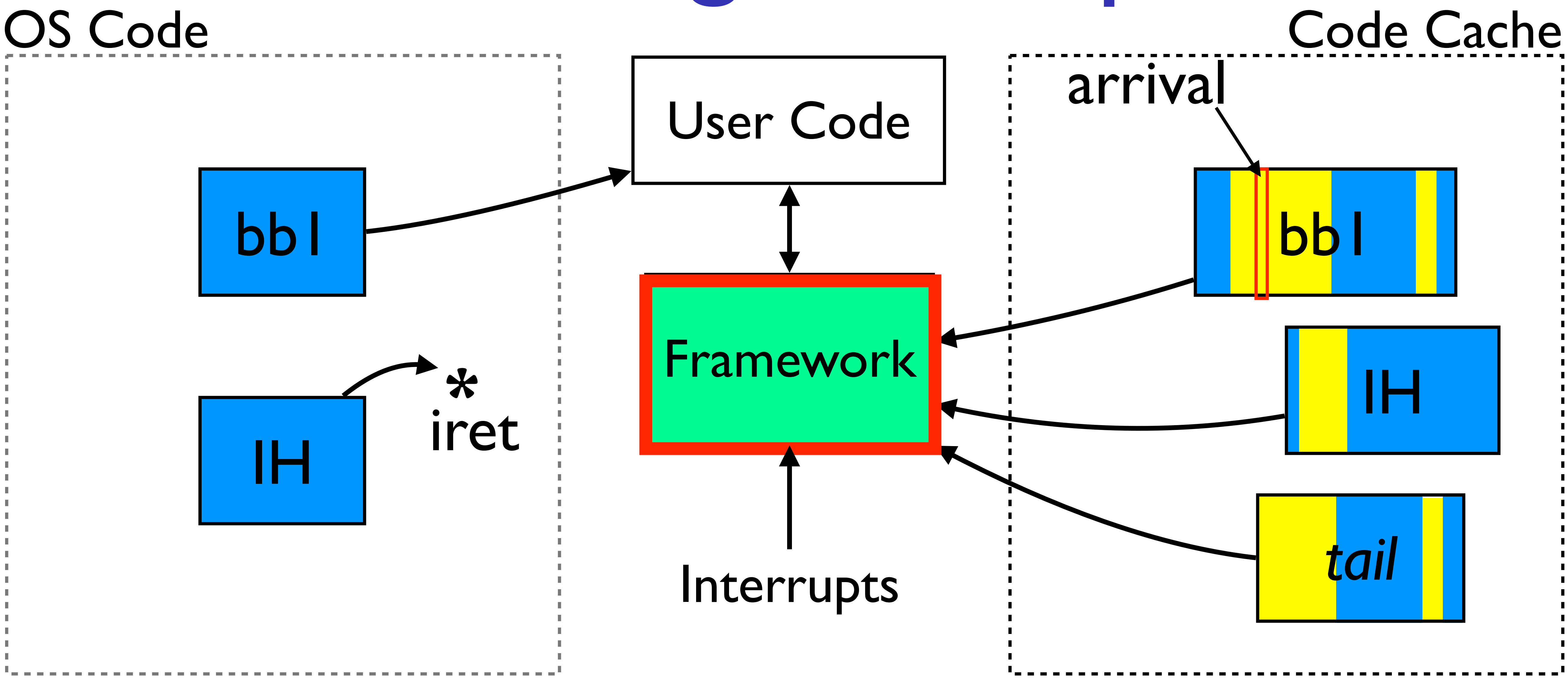

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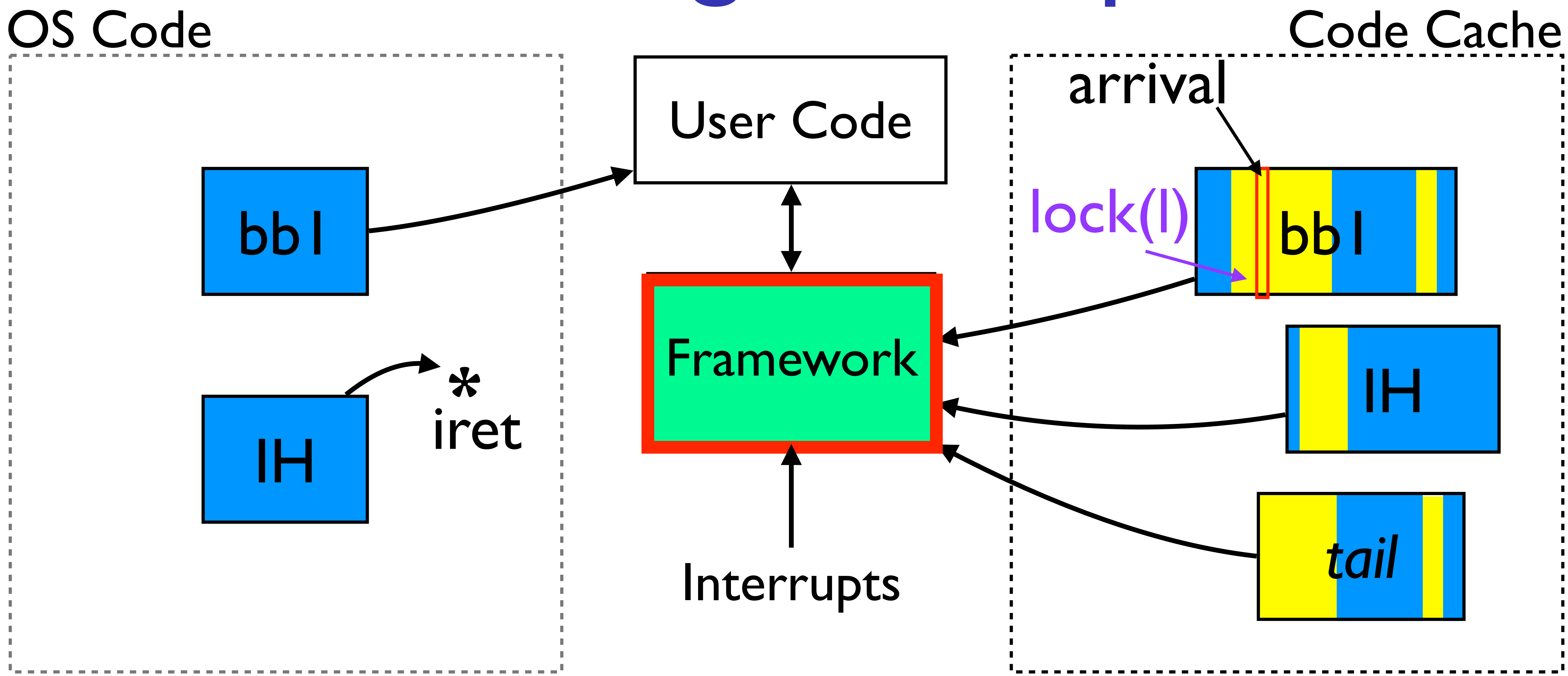

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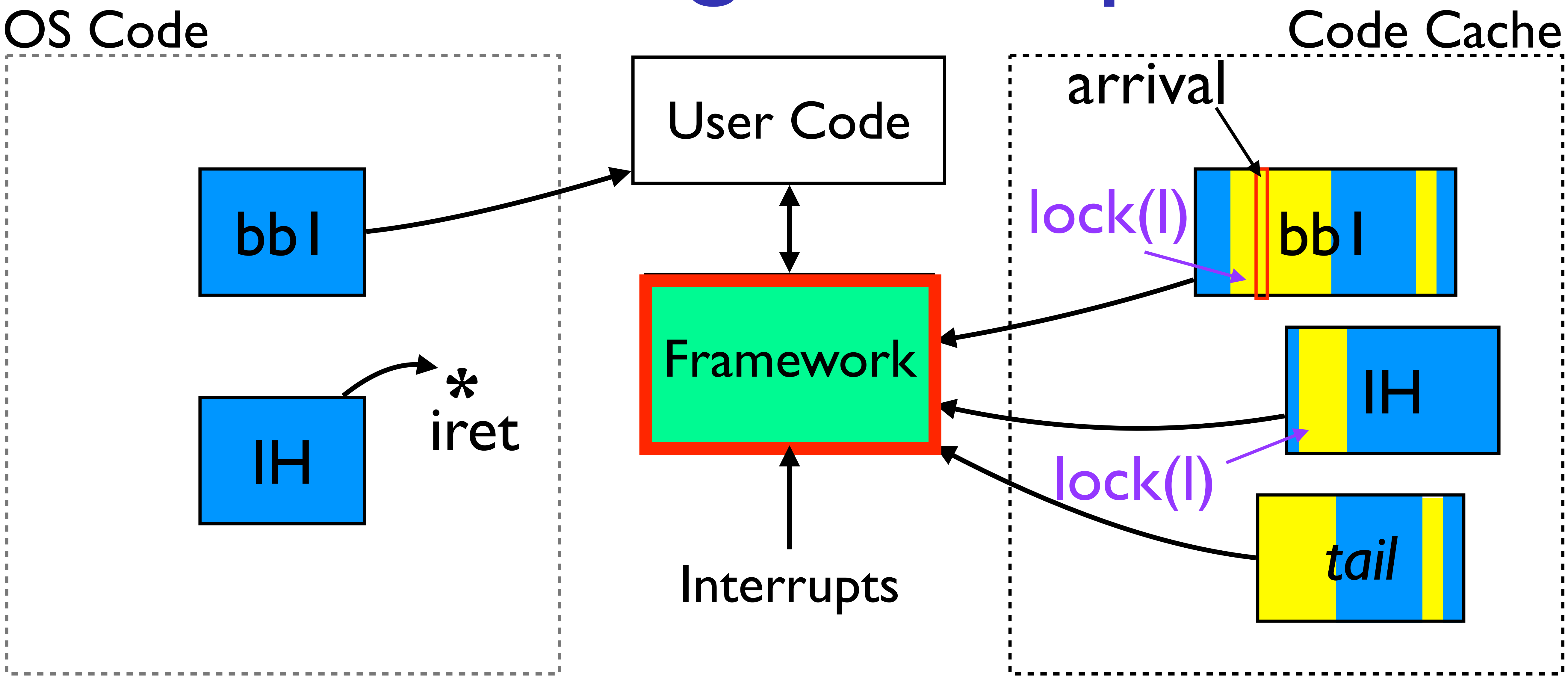

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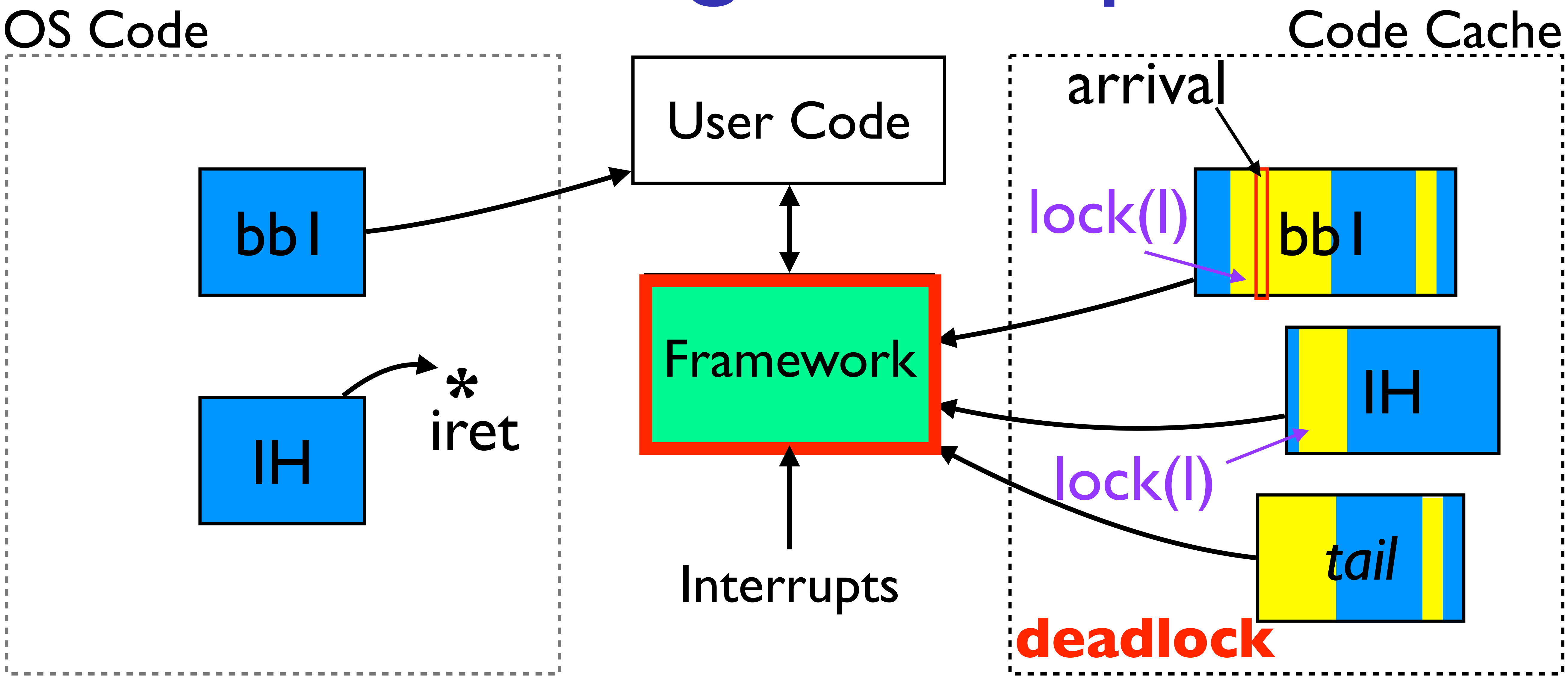

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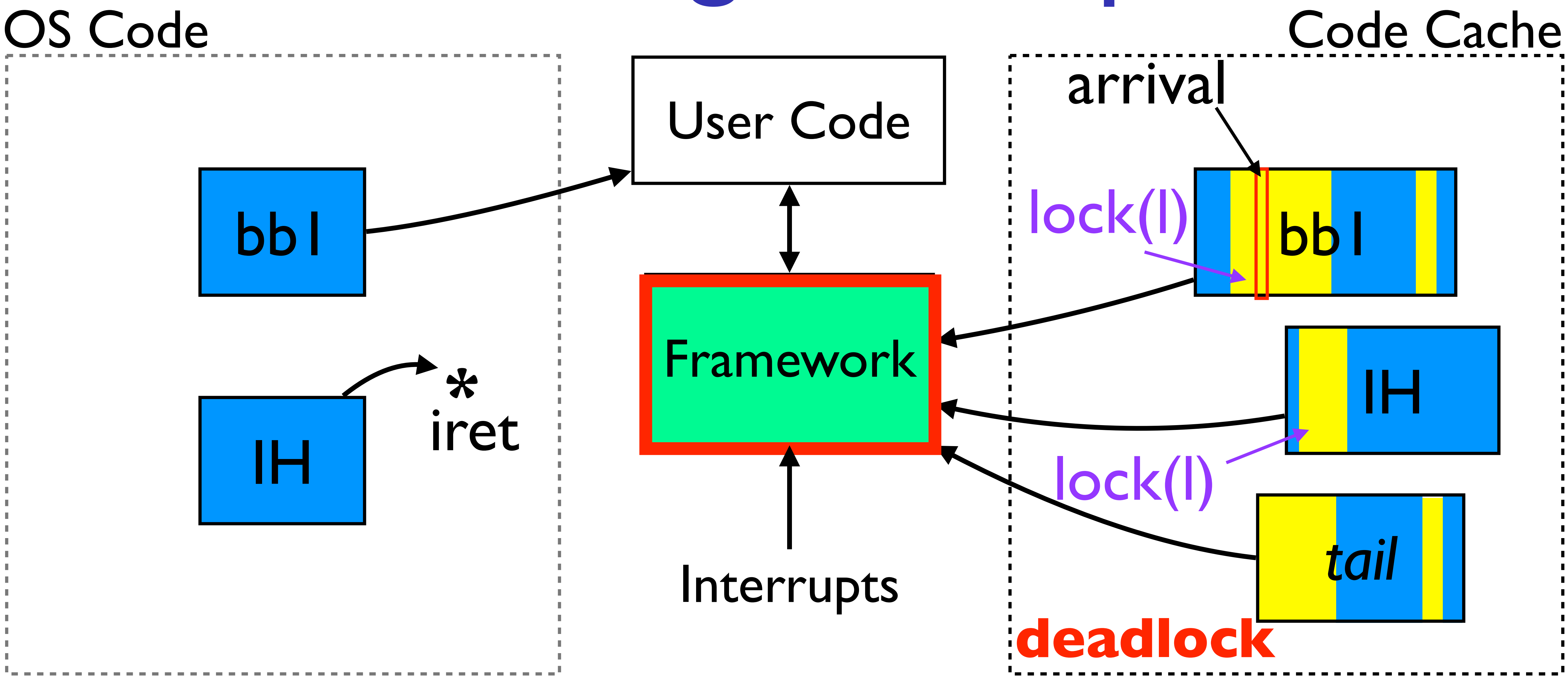

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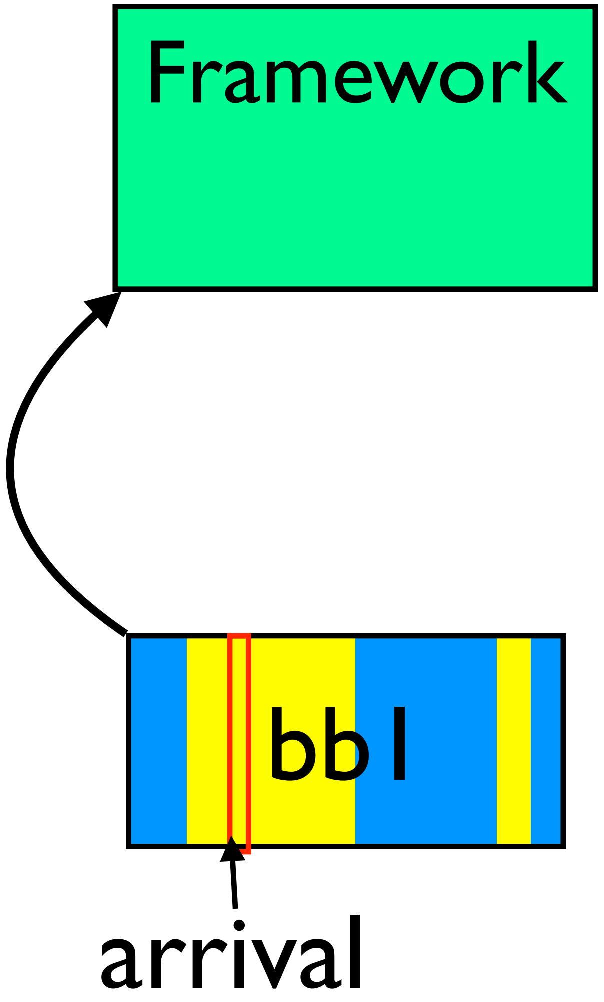
Need to delay

Delaying Interrupts



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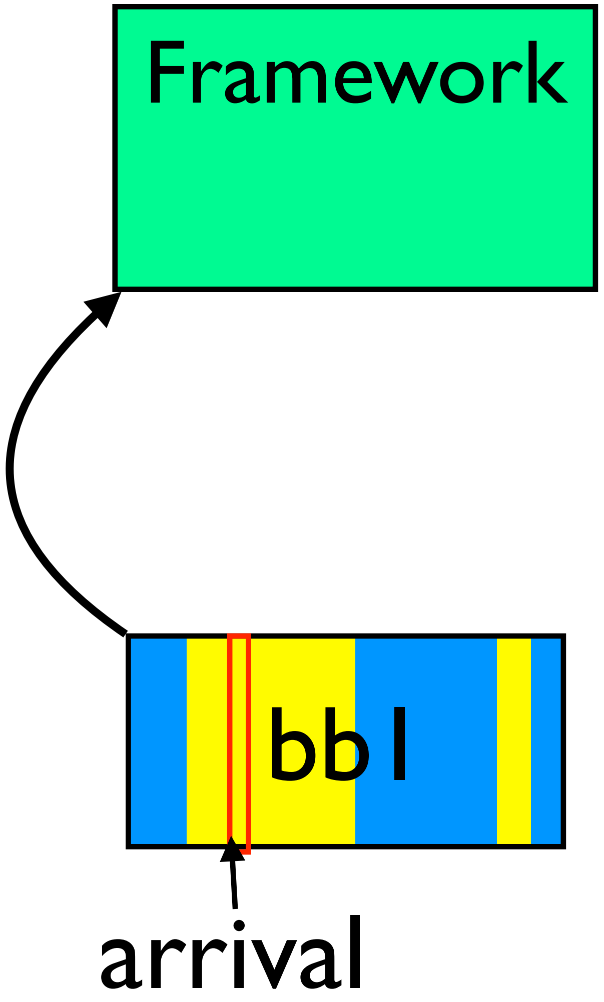

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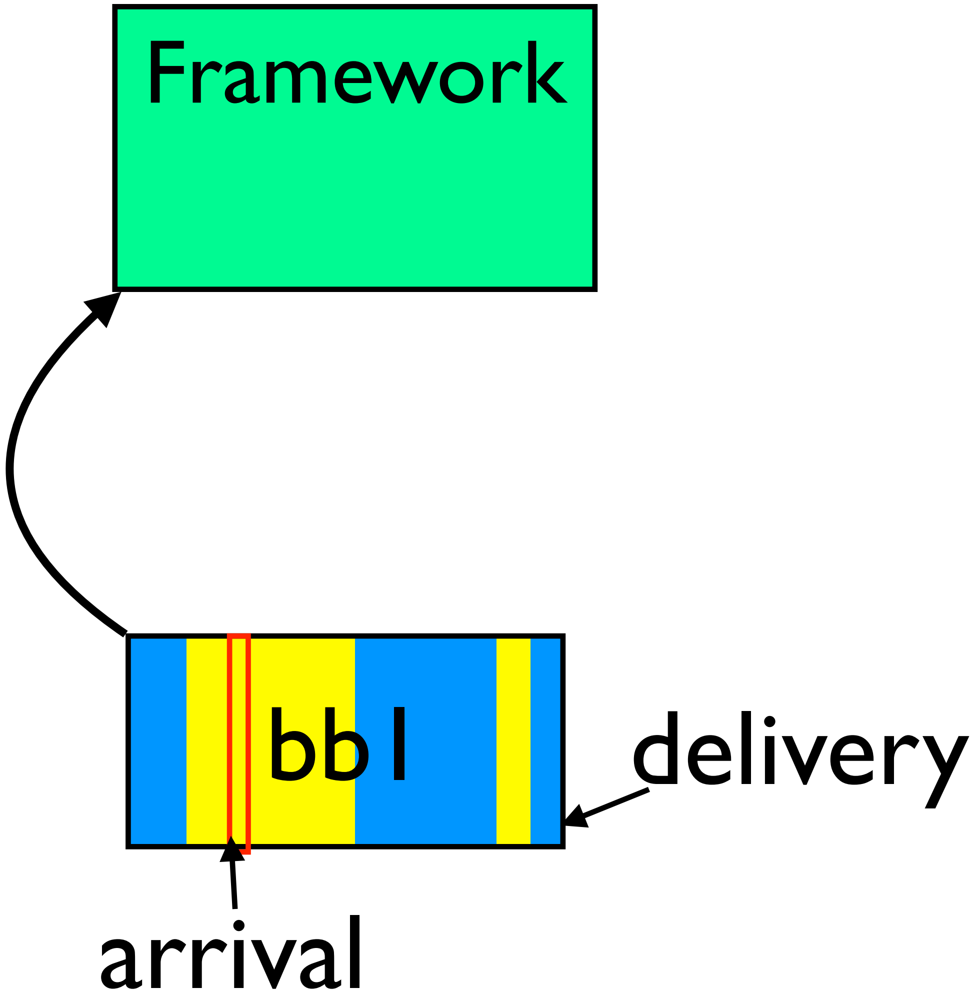
Delay until end of bb1?



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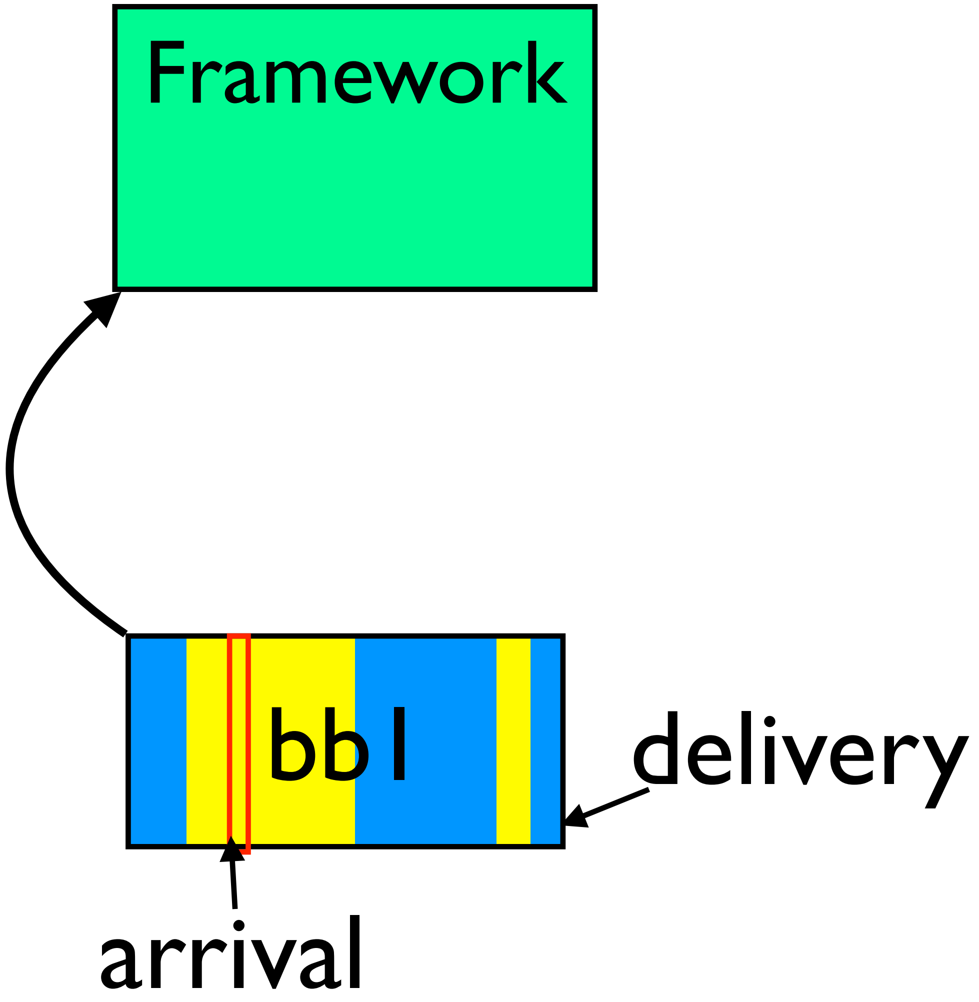

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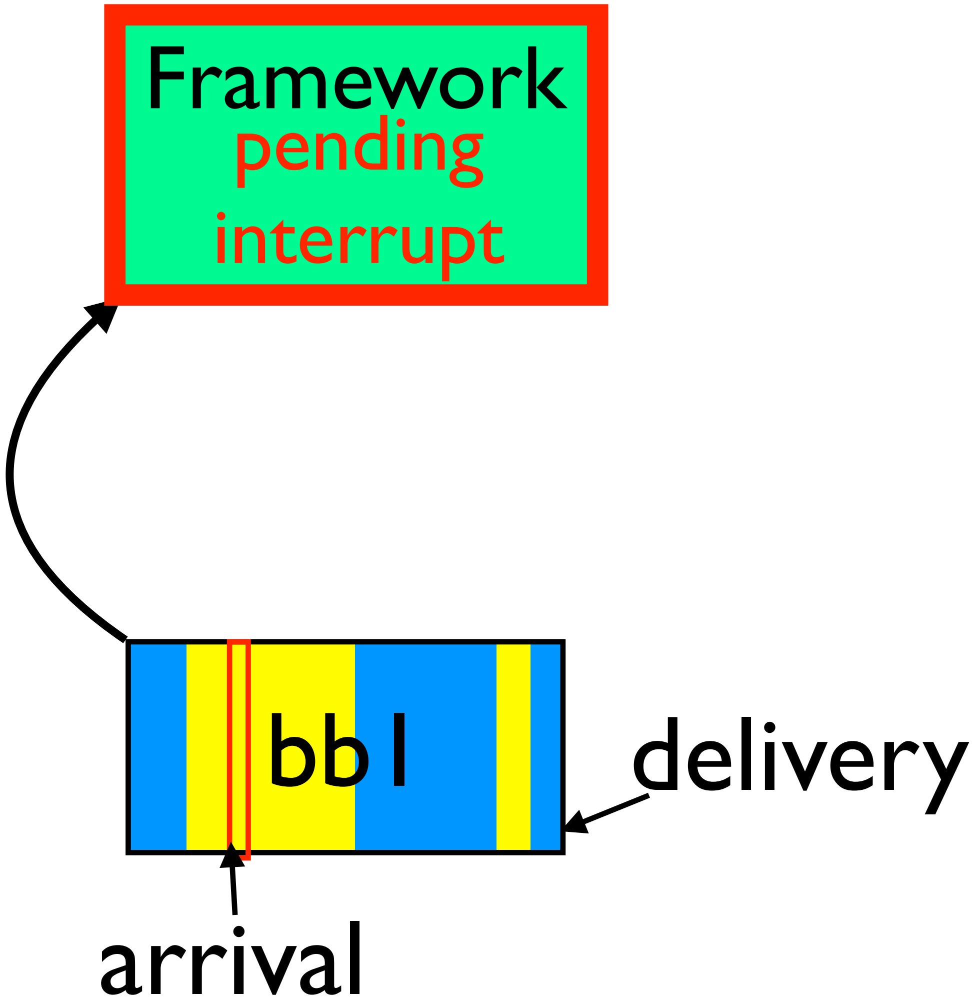

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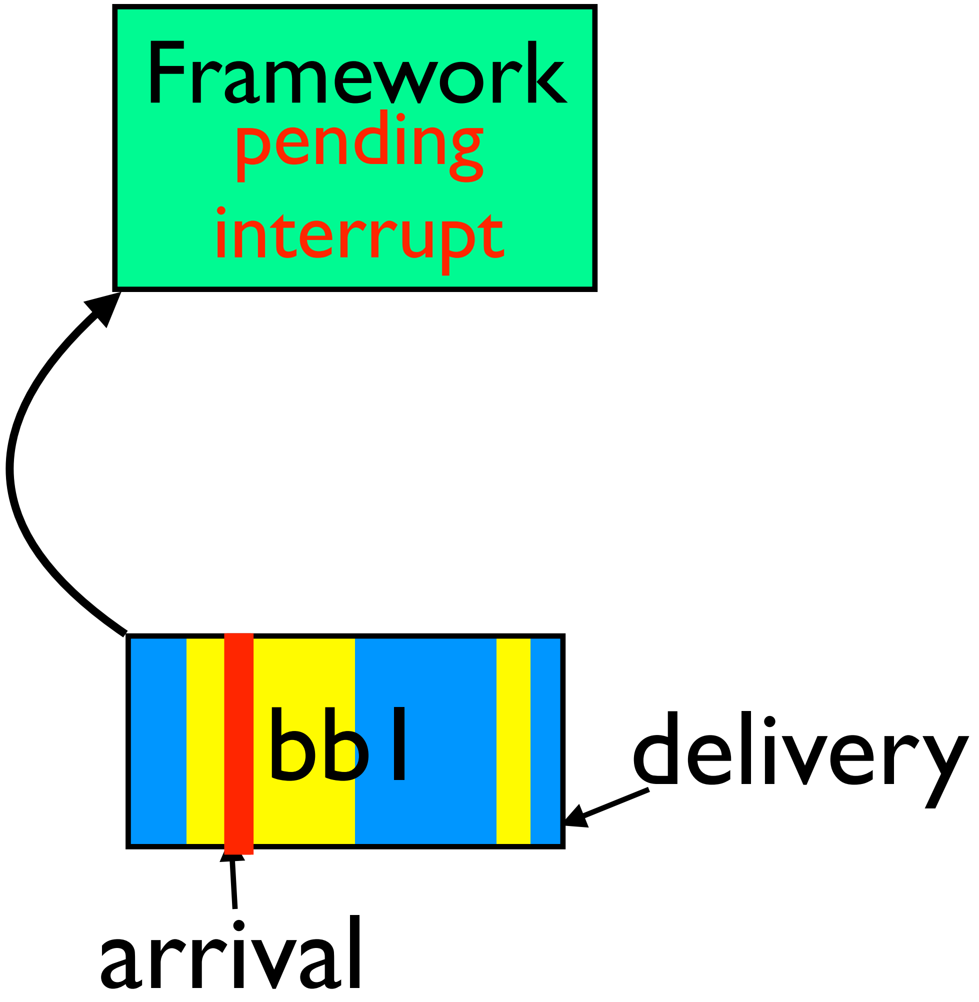

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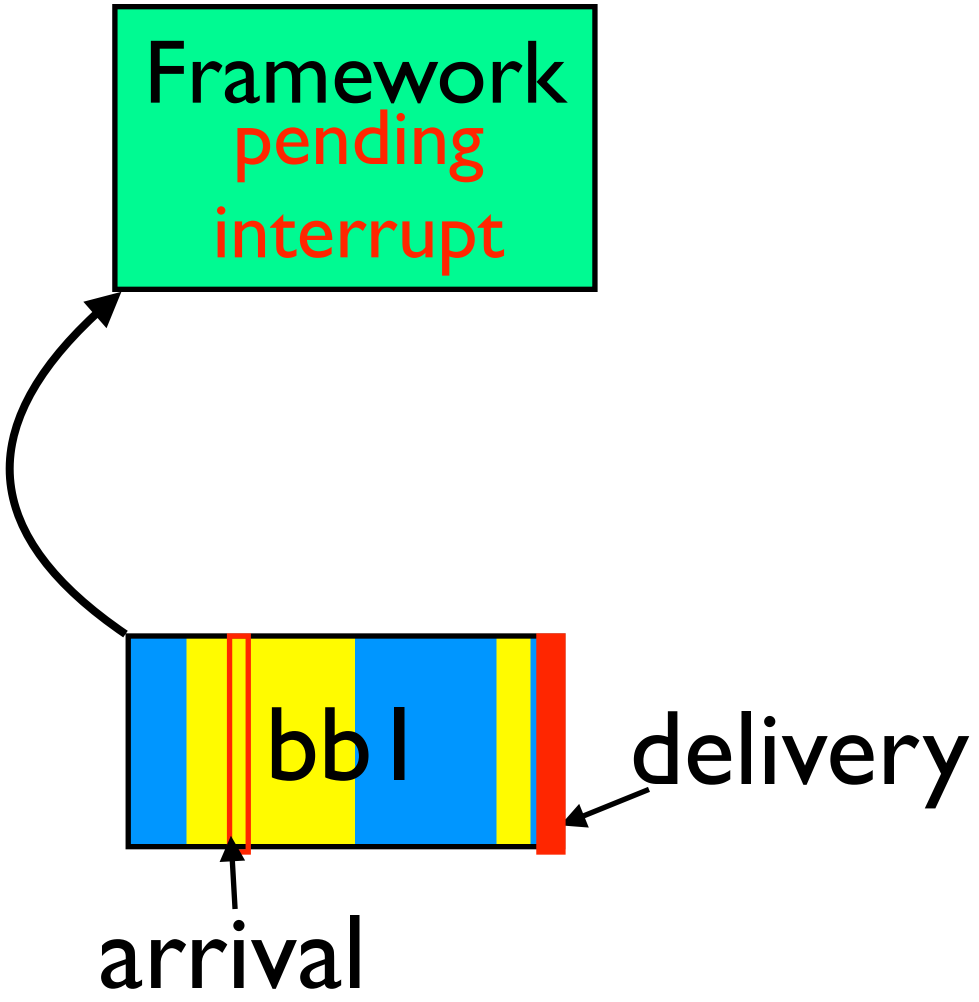

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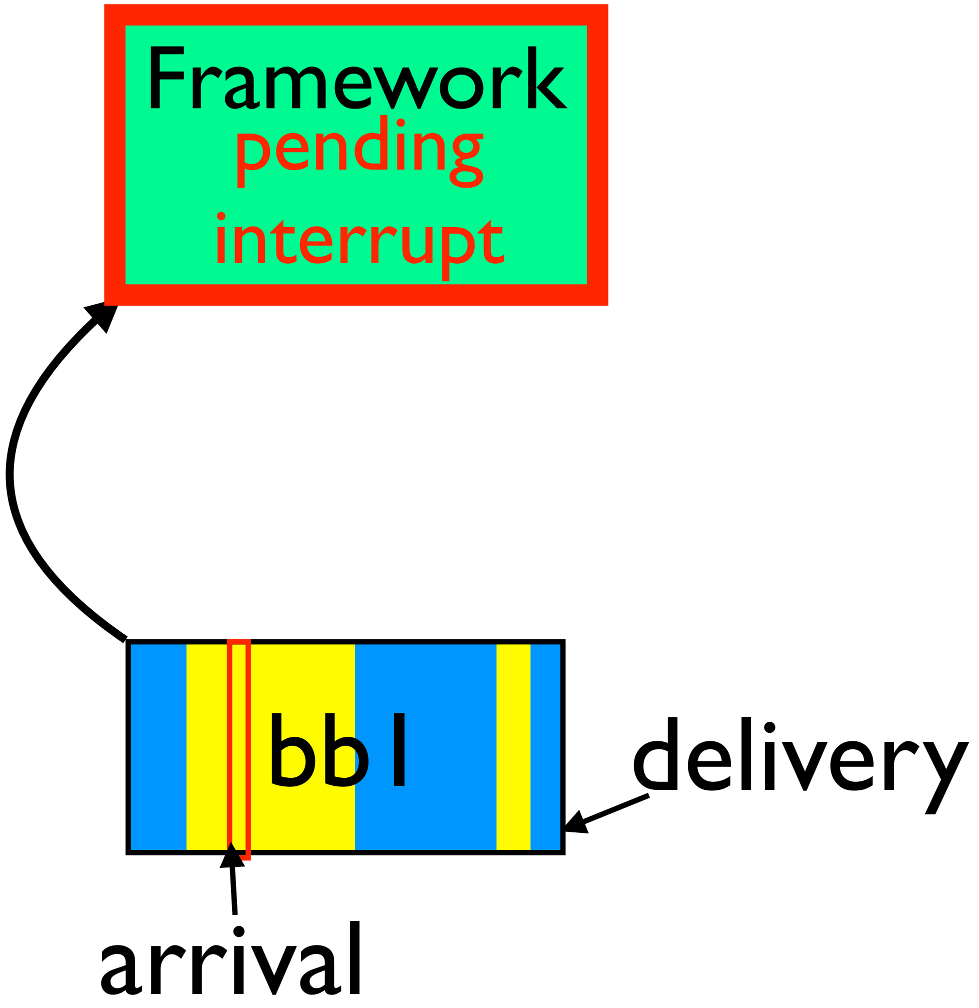

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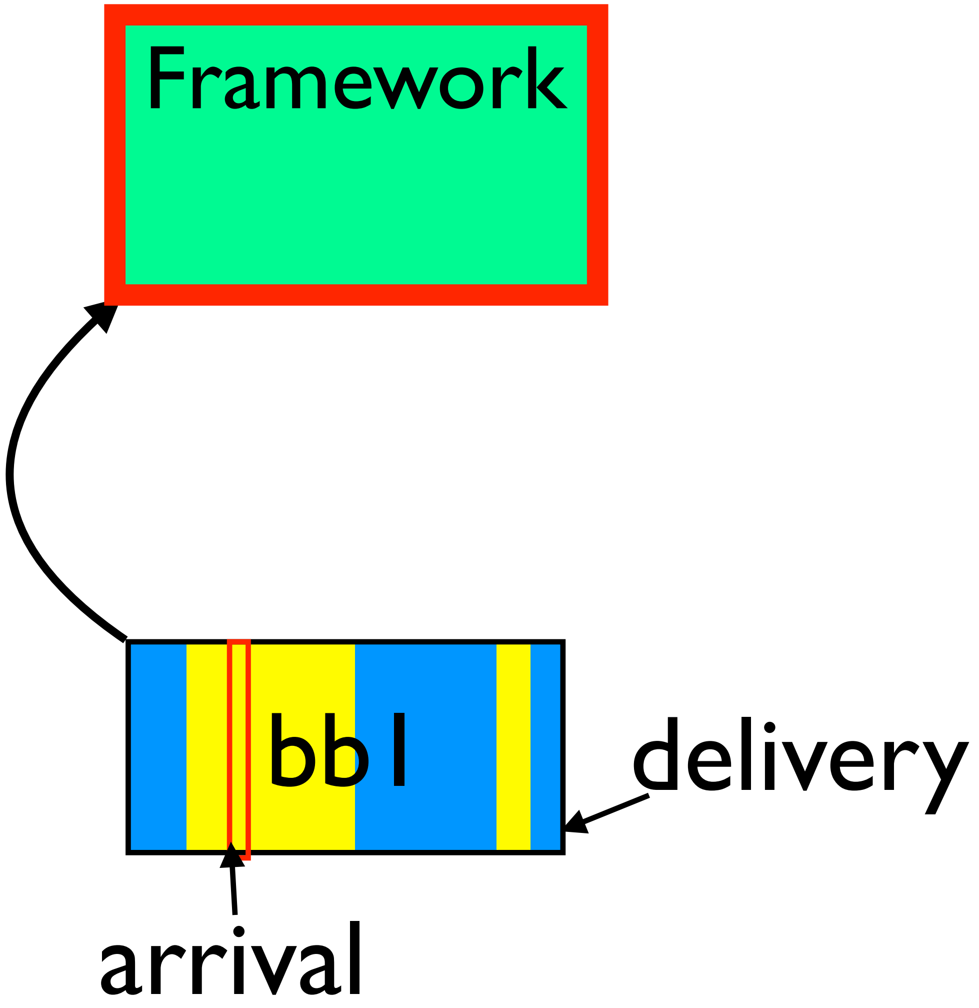

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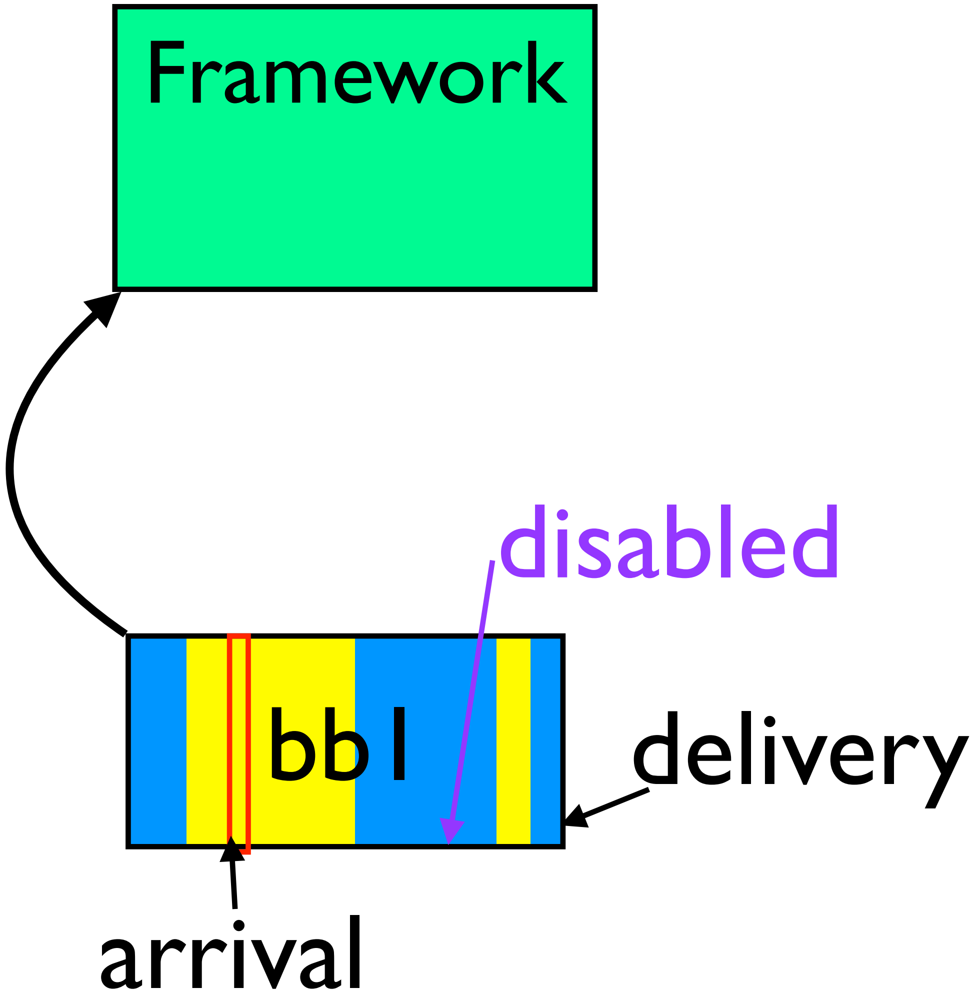

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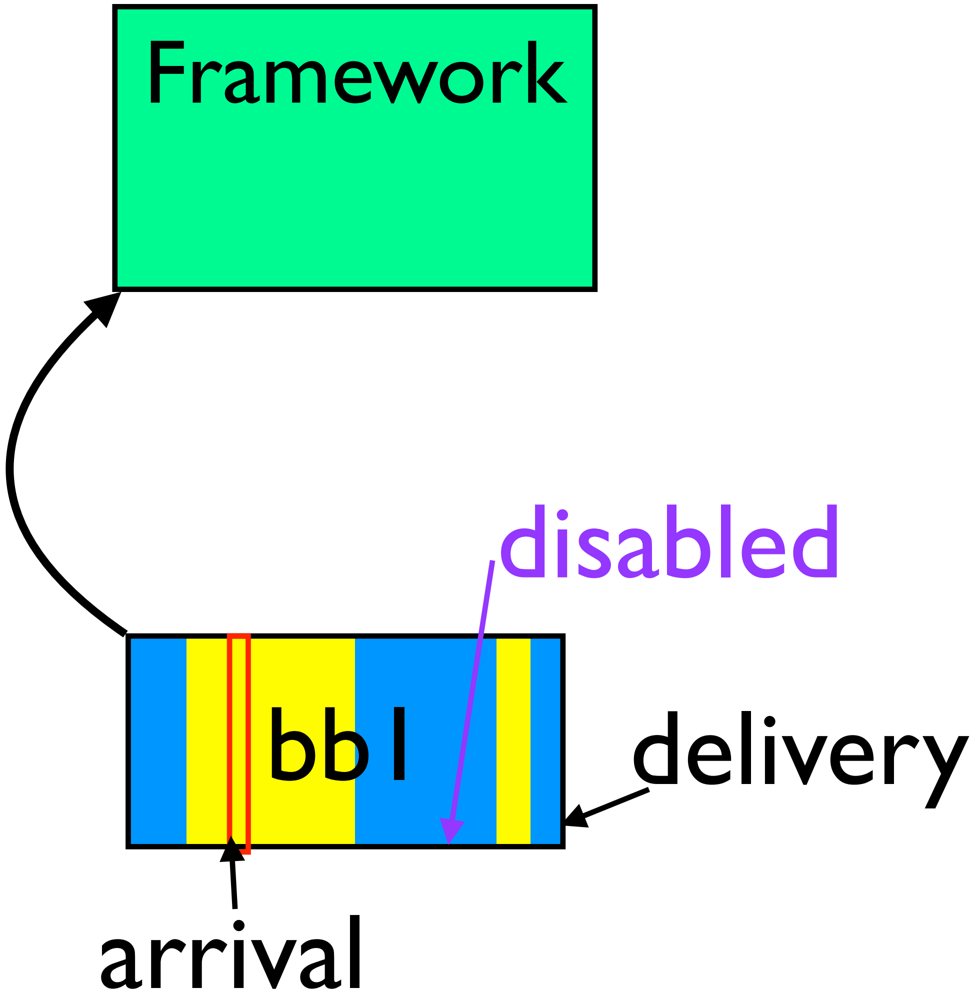
Delay until end of bb1?

- Avoids tail
- Problem if bb1 disables interrupt
  - Could be any MMIO
  - Framework cannot detect if enabled

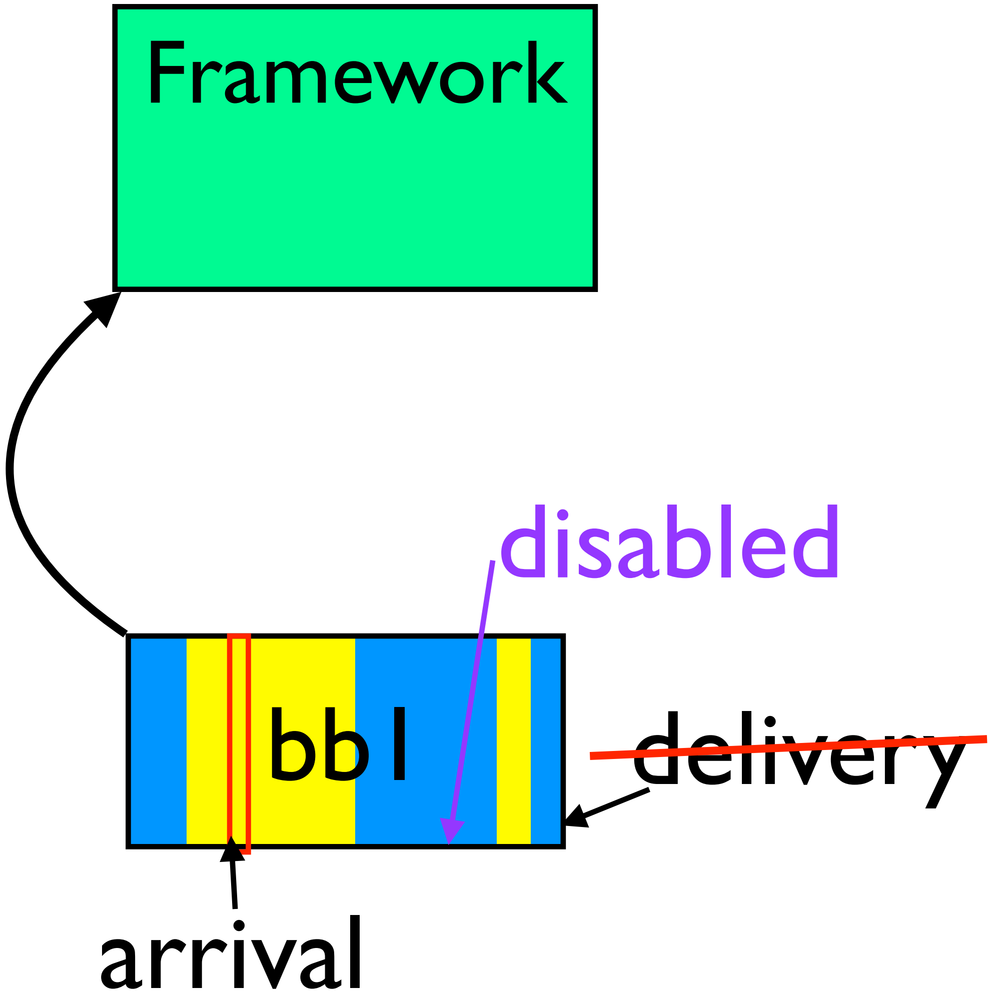


Delaying Interrupts

Where do we delay it until?

Delay until end of bb1? ✗

- Avoids tail
- Problem if bb1 disables interrupt
  - Could be any MMIO
  - Framework cannot detect if enabled



Framework

disabled

bb1

~~delivery~~

arrival

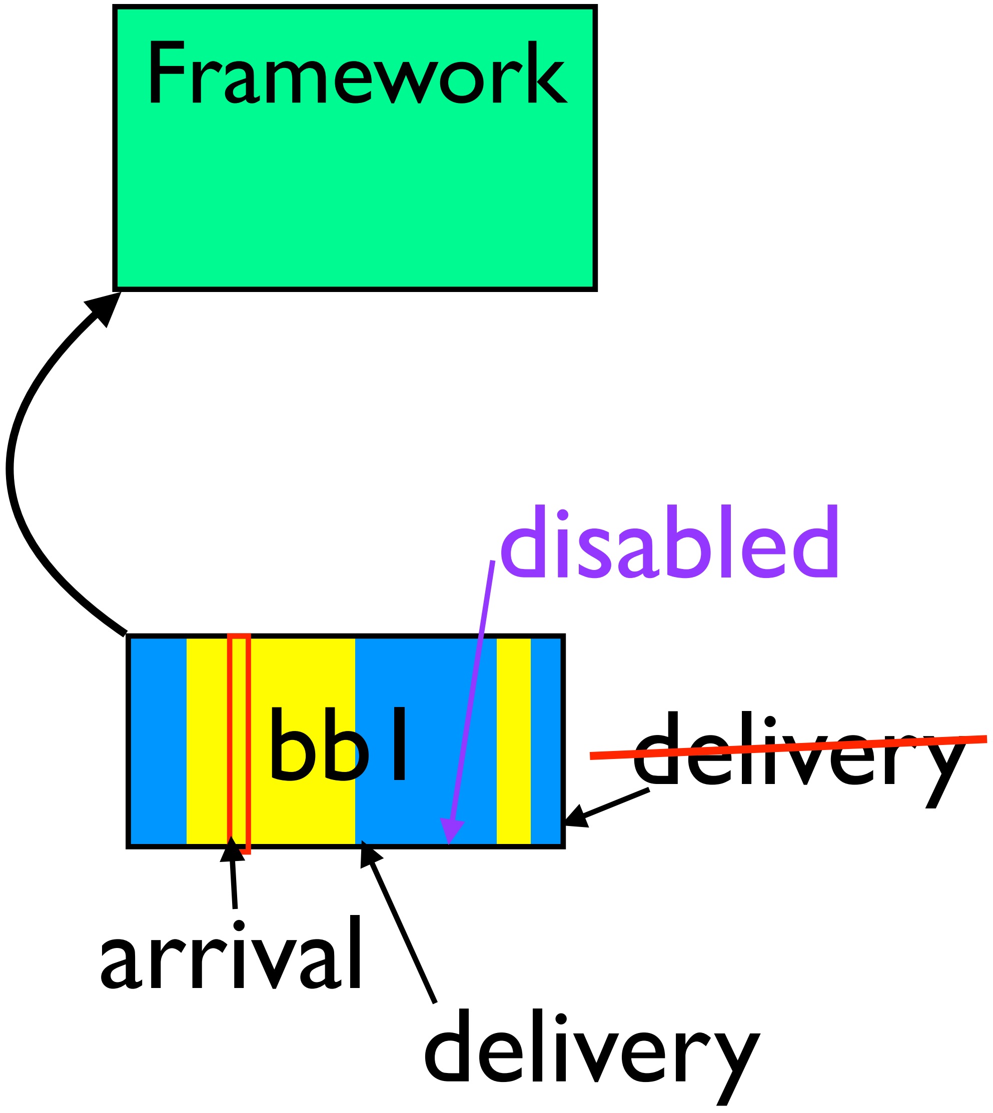
Delaying Interrupts

Where do we delay it until?

Delay until end of bb1? ✗

- Avoids tail
- Problem if bb1 disables interrupt
  - Could be any MMIO
  - Framework cannot detect if enabled

Must deliver before next OS instruction



Delaying Interrupts

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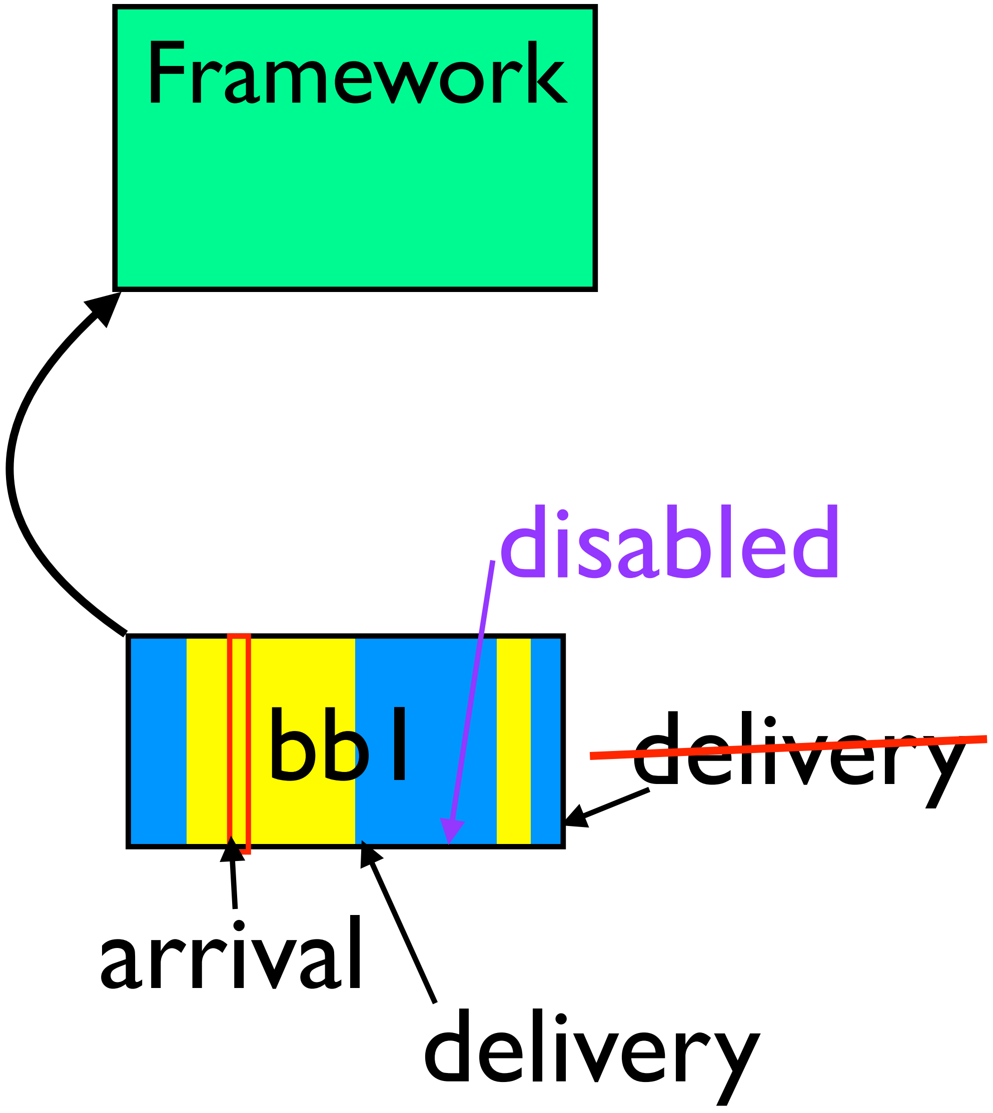

Must deliver before next OS instruction

- Delay until end of instrumentation

Delaying Interrupts

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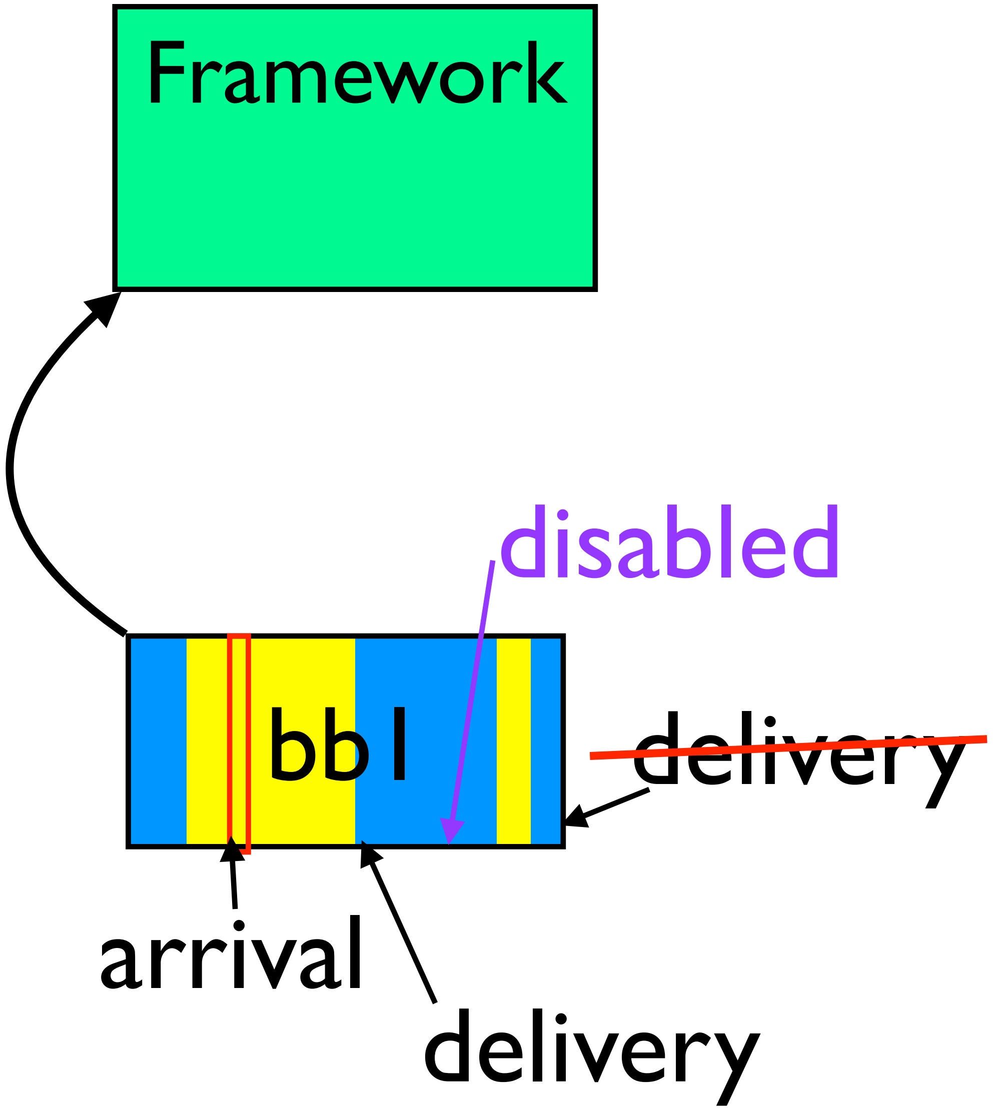
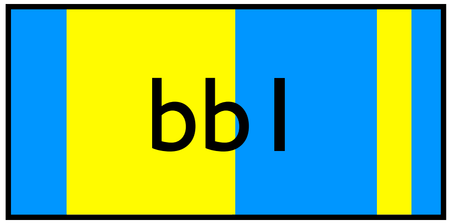


Must deliver before next OS instruction

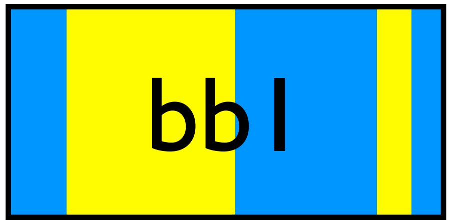
- Delay until end of instrumentation
- Still duplicates tail

How to Delay Interrupts



How to Delay Interrupts

Could disable them on the CPU



How to Delay Interrupts

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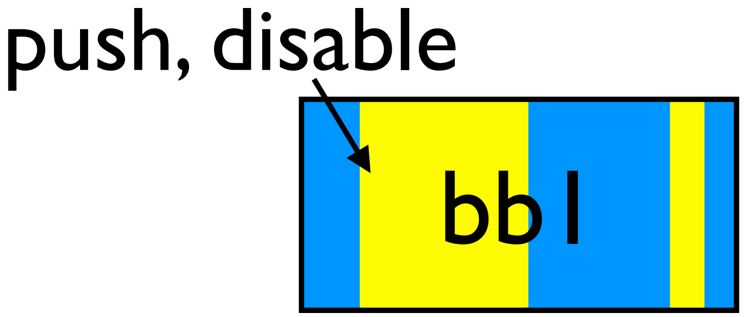

How to Delay Interrupts

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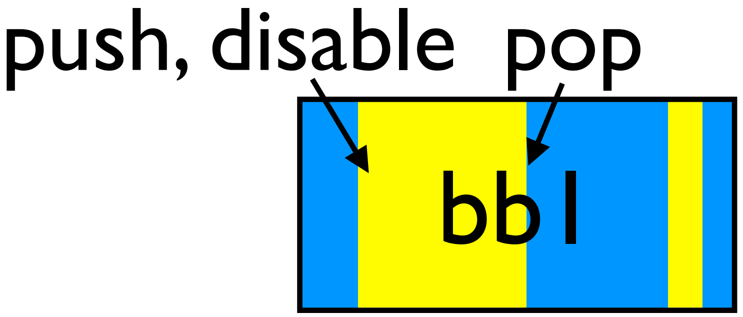

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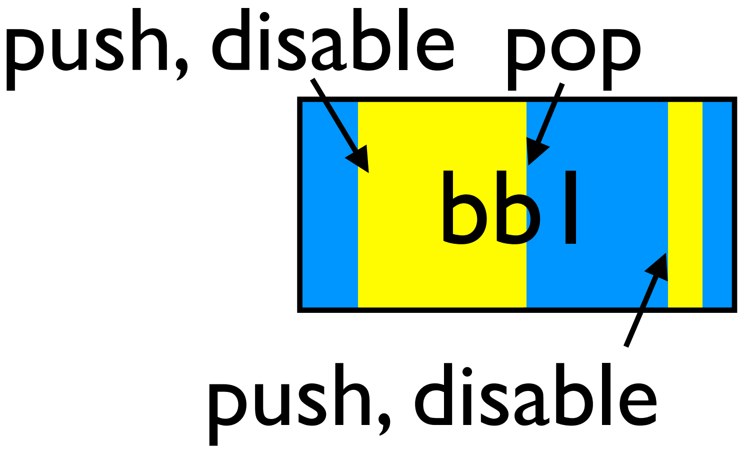

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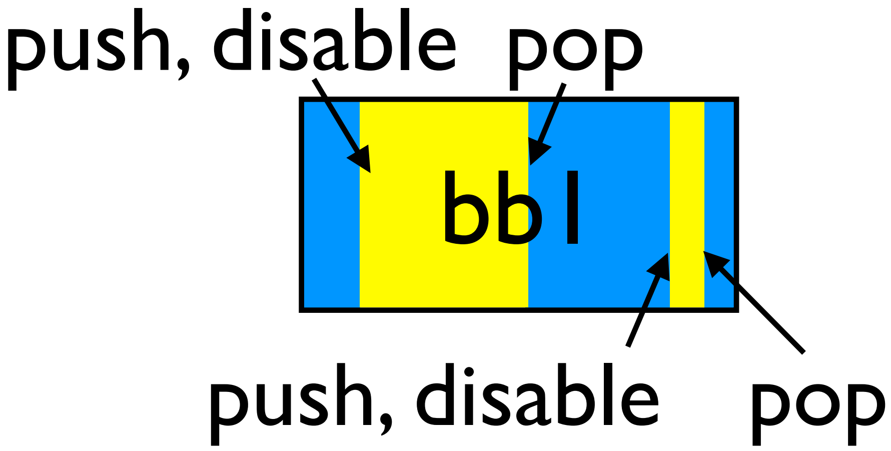

How to Delay Interrupts

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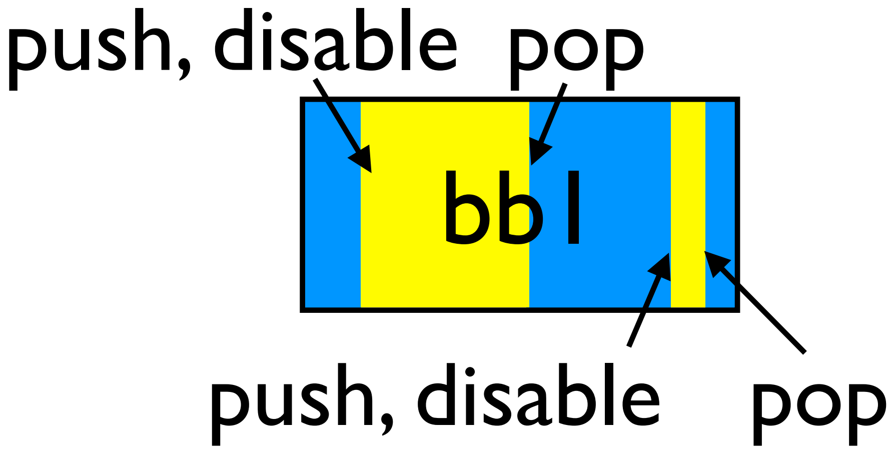
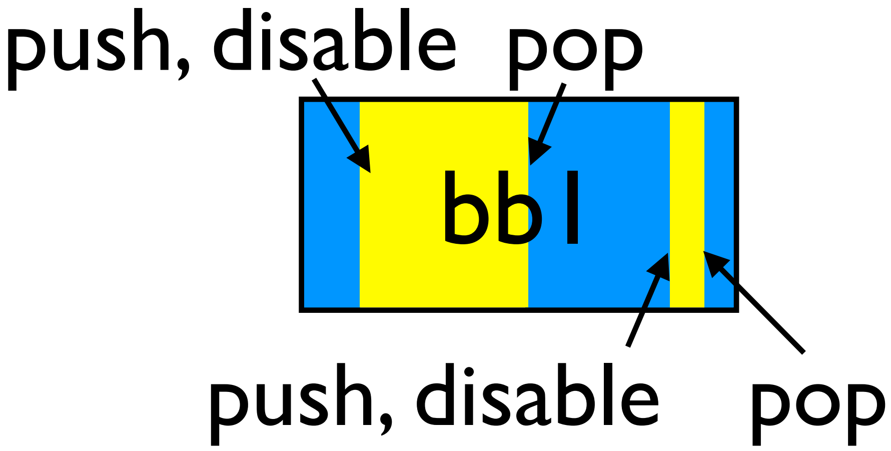


But performance would be bad

How to Delay Interrupts

Could disable them on the CPU



But performance would be bad

Instead, have framework handle it

- Extra overhead for interrupt, cheaper instrumentation

How to Delay Interrupts

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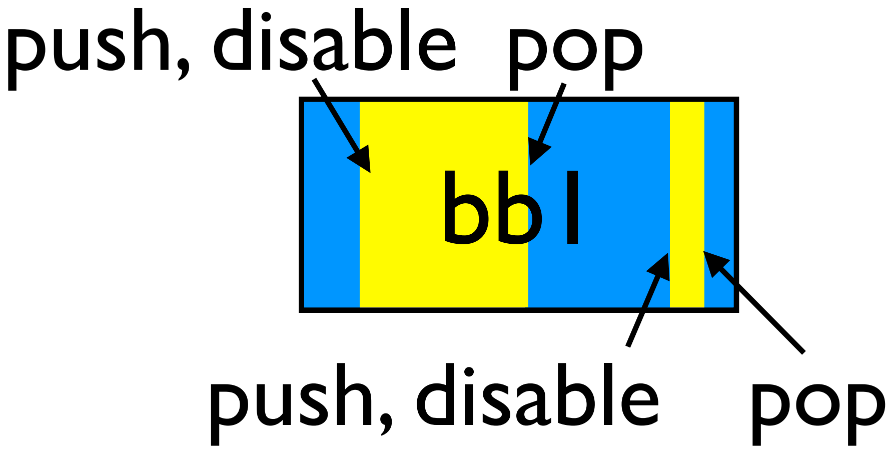


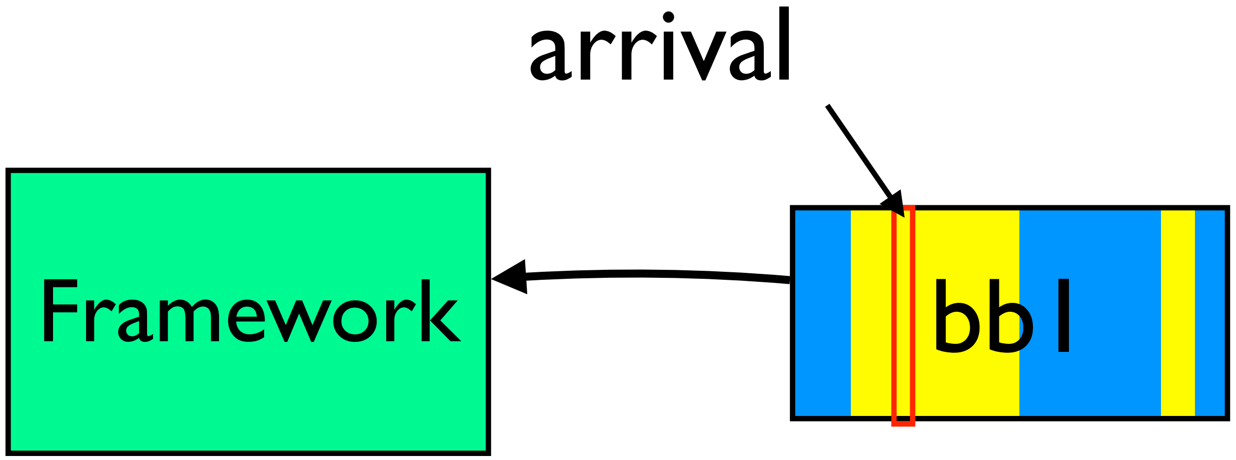
But performance would be bad

Instead, have framework handle it

- Extra overhead for interrupt, cheaper instrumentation
- Instrumentation more frequent than interrupts
- Gigabit NIC sends interrupt every 100μs ≈ 100K instr.

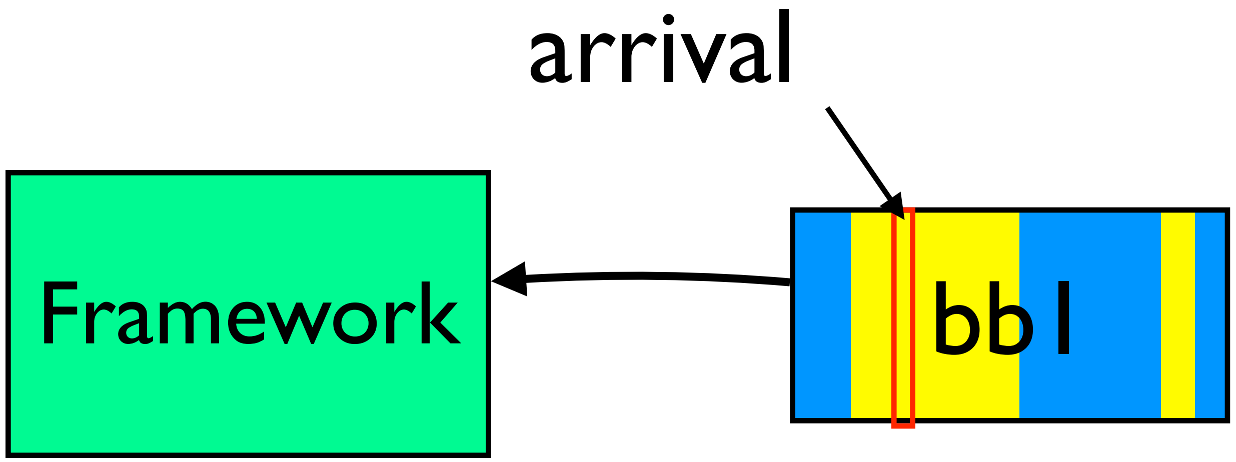
Delaying with Patches

Example: interrupt 239



Delaying with Patches

Example: interrupt 239

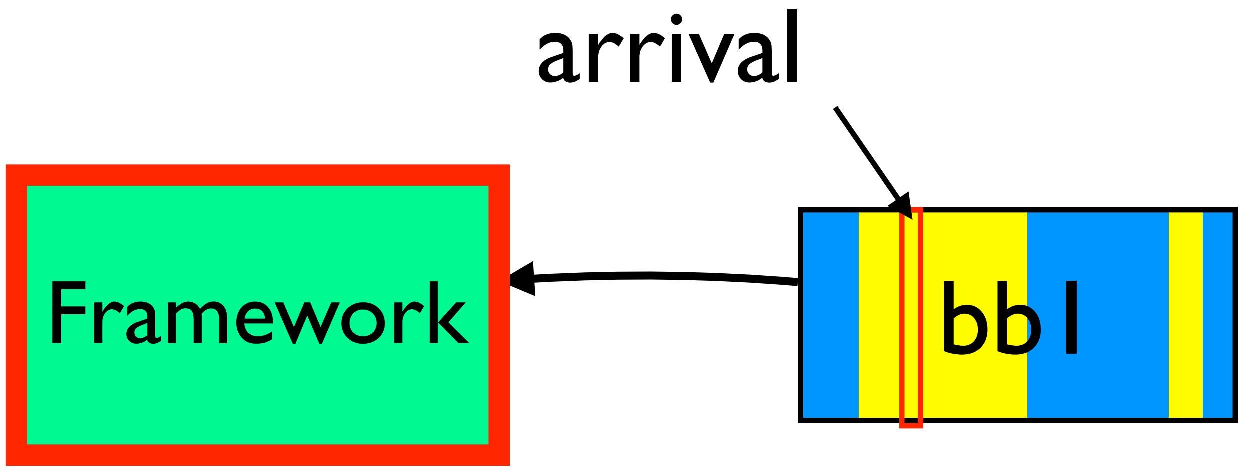


Interrupt Stack Frame

Interrupts enabled	yes
...	

Delaying with Patches

Example: interrupt 239



Interrupt Stack Frame

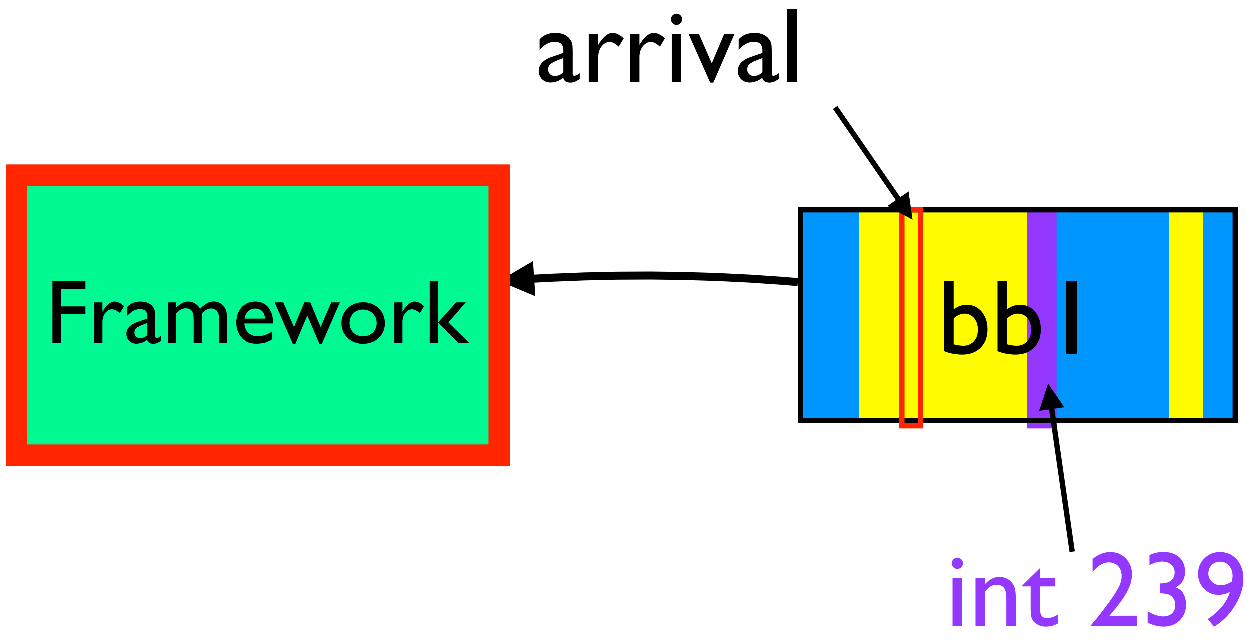
Interrupts enabled	yes
...	

Delaying with Patches

Example: interrupt 239

The framework

1. Patches next native instruction

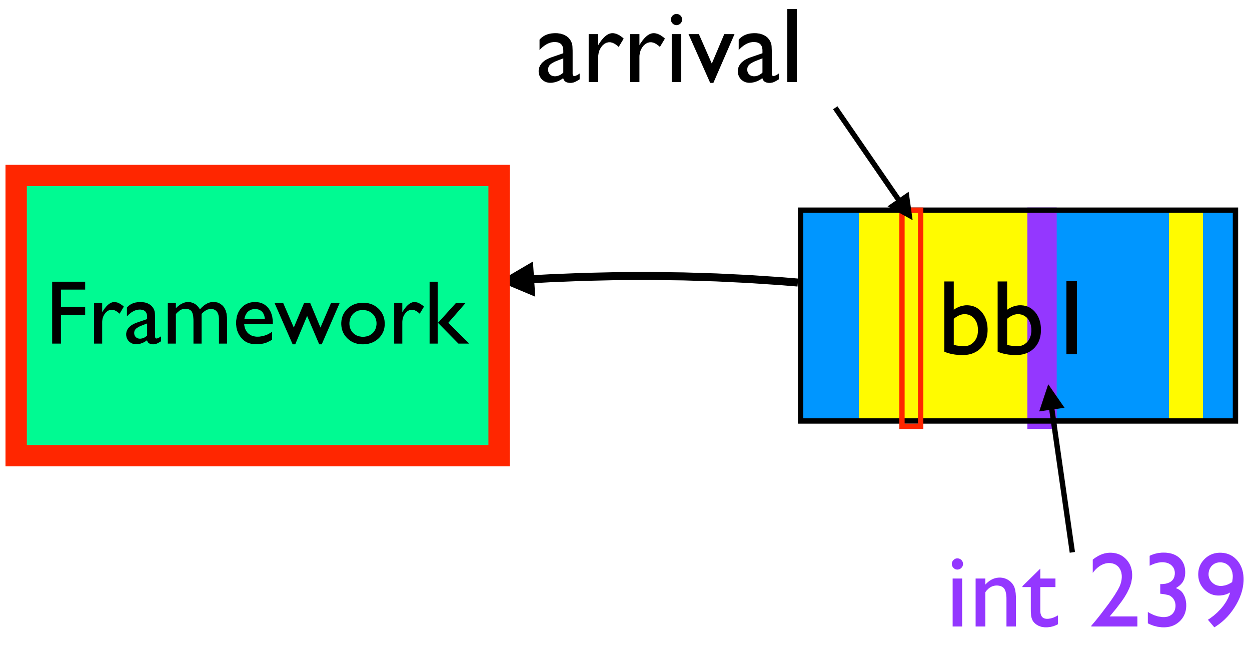


Interrupt Stack Frame

Interrupts enabled	yes
...	

Delaying with Patches

Example: interrupt 239



The framework

1. Patches next native instruction
2. Disables interrupts on iret

Interrupt Stack Frame

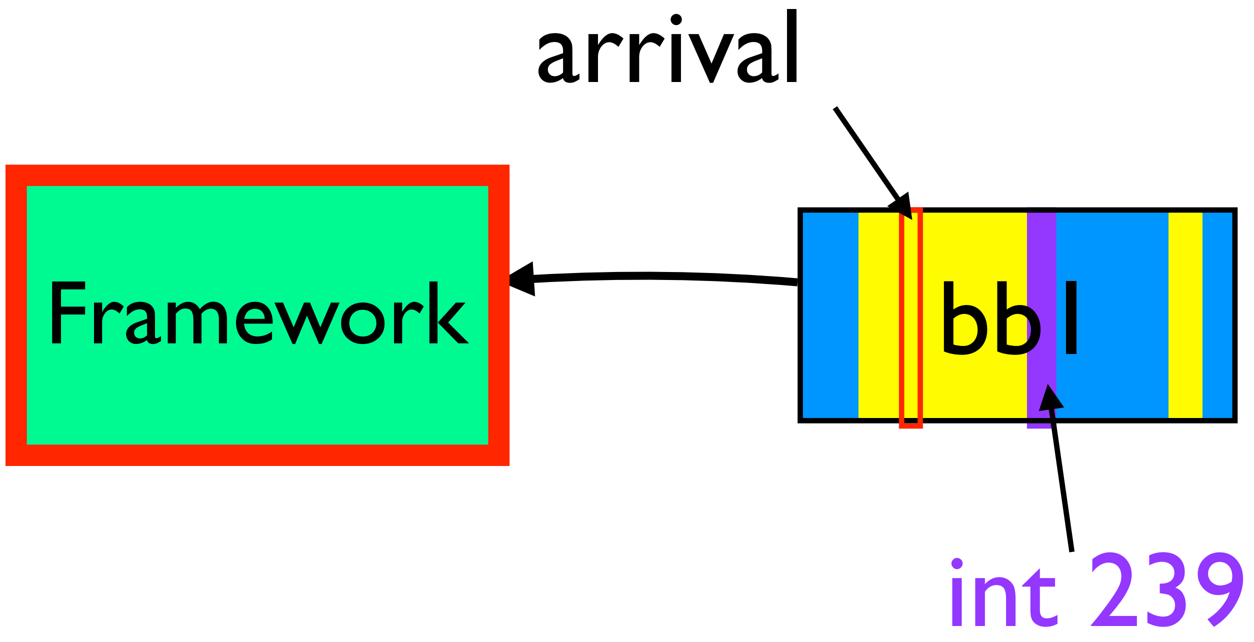
Interrupts enabled	~~yes~~ no
...	

Delaying with Patches

Example: interrupt 239

The framework

1. Patches next native instruction
2. Disables interrupts on iret
3. iret



Interrupt Stack Frame

Interrupts enabled	~~yes~~ no
...	

Delaying with Patches

Example: interrupt 239

The framework

1. Patches next native instruction
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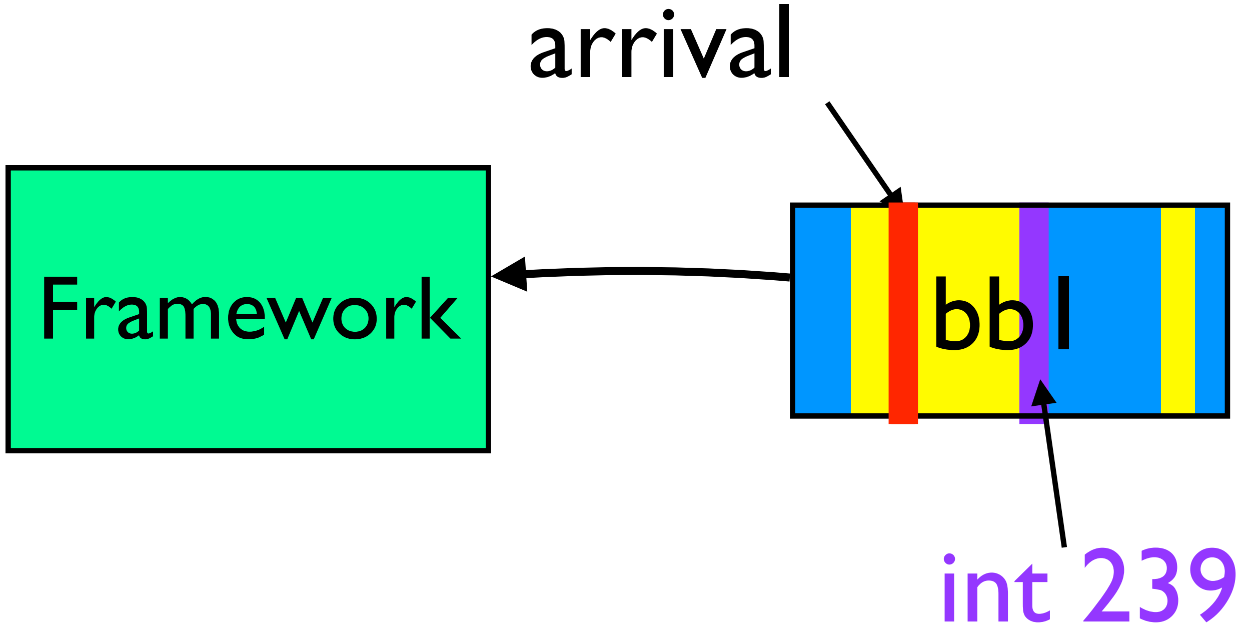

Interrupt Stack Frame

Interrupts enabled	~~yes~~ no
...	

Delaying with Patches

Example: interrupt 239

The framework

1. Patches next native instruction
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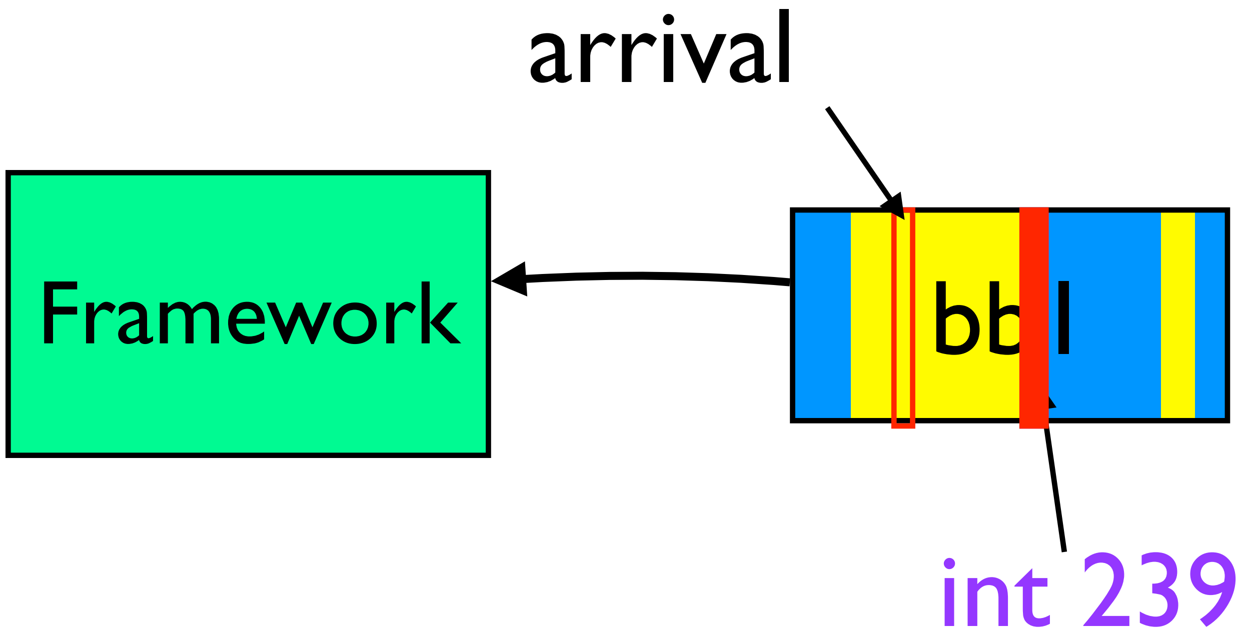
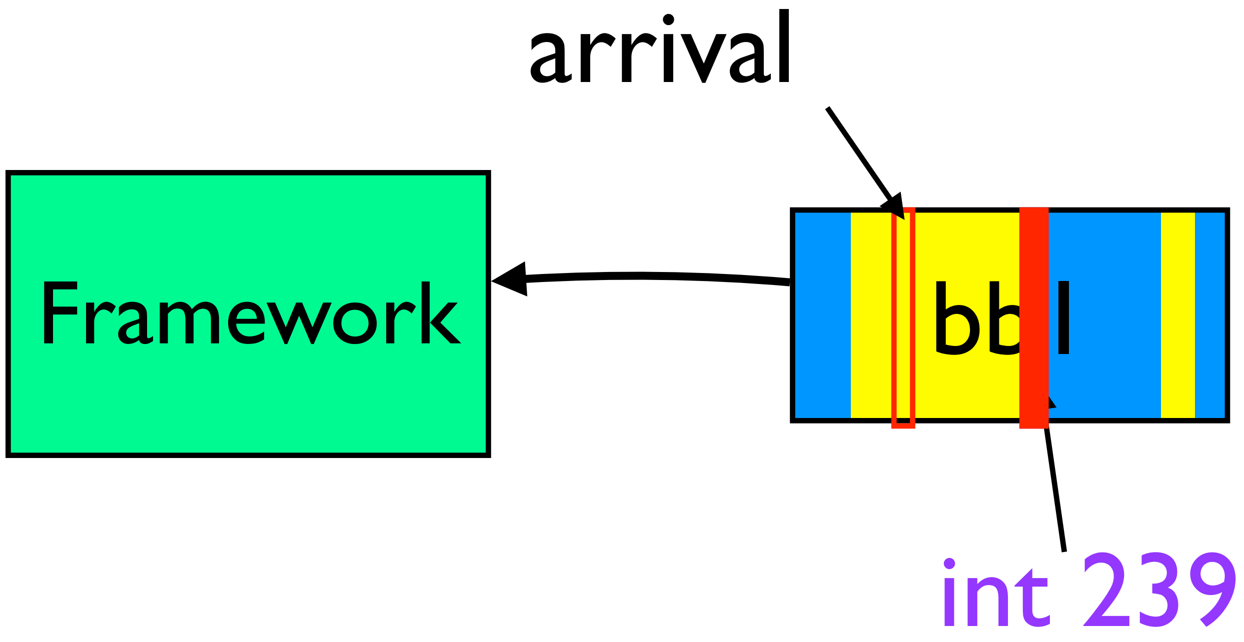


Interrupt Stack Frame

Interrupts enabled	~~yes~~ no
...	

Delaying with Patches

Example: interrupt 239



The framework

1. Patches next native instruction
2. Disables interrupts on iret
3. iret

Interrupt Stack Frame

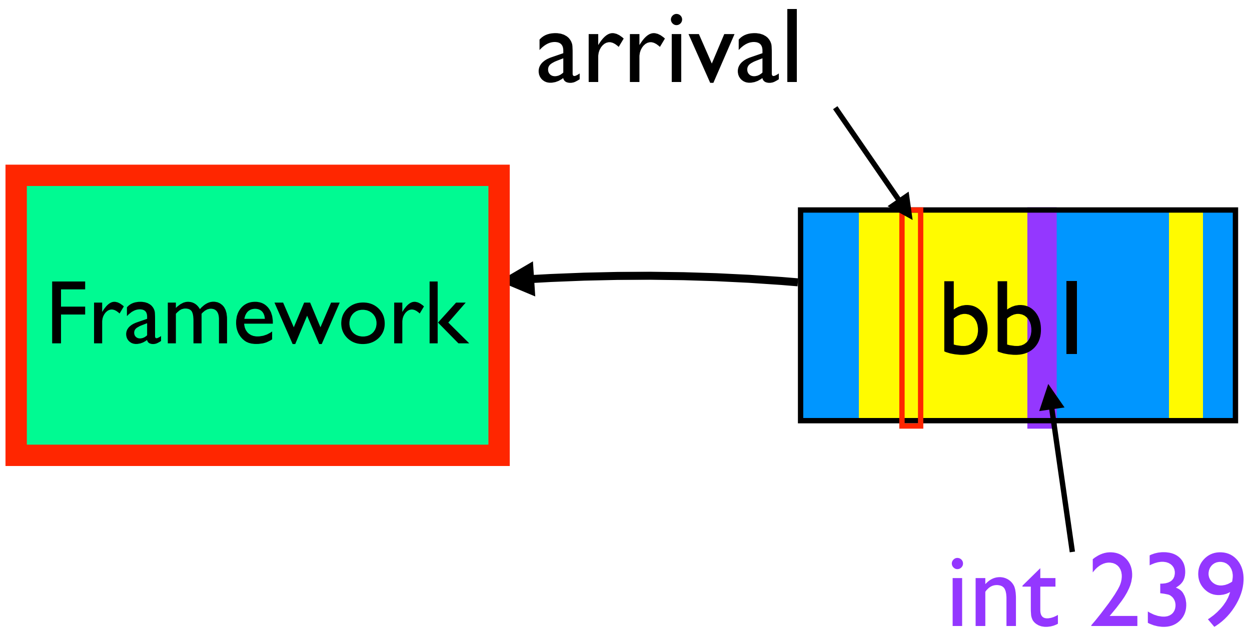
Interrupts enabled	no ~~yes~~
...	

Patch Interrupt Stack Frame

Interrupts enabled	no
...	

Delaying with Patches

Example: interrupt 239



The framework

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2. Disables interrupts on iret
3. iret

Interrupt Stack Frame

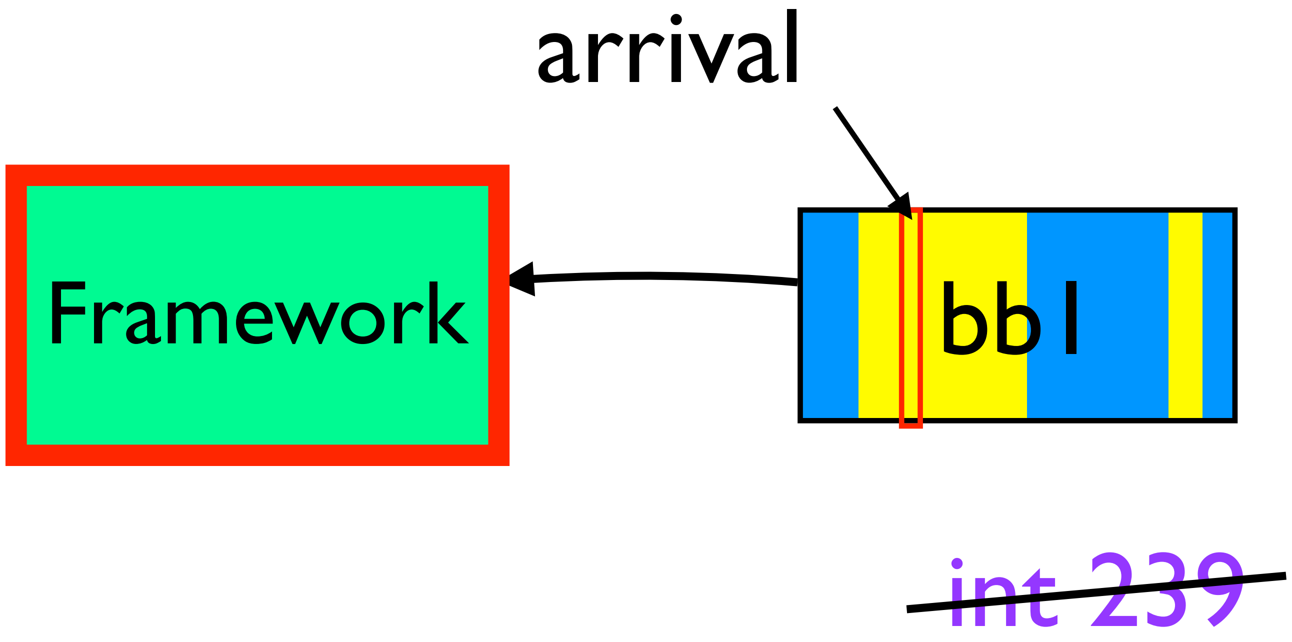
Interrupts enabled	~~yes~~ no
...	

Patch Interrupt Stack Frame

Interrupts enabled	no
...	

Delaying with Patches

Example: interrupt 239



The framework

1. Patches next native instruction
2. Disables interrupts on iret
3. iret
4. Removes patch

Interrupt Stack Frame

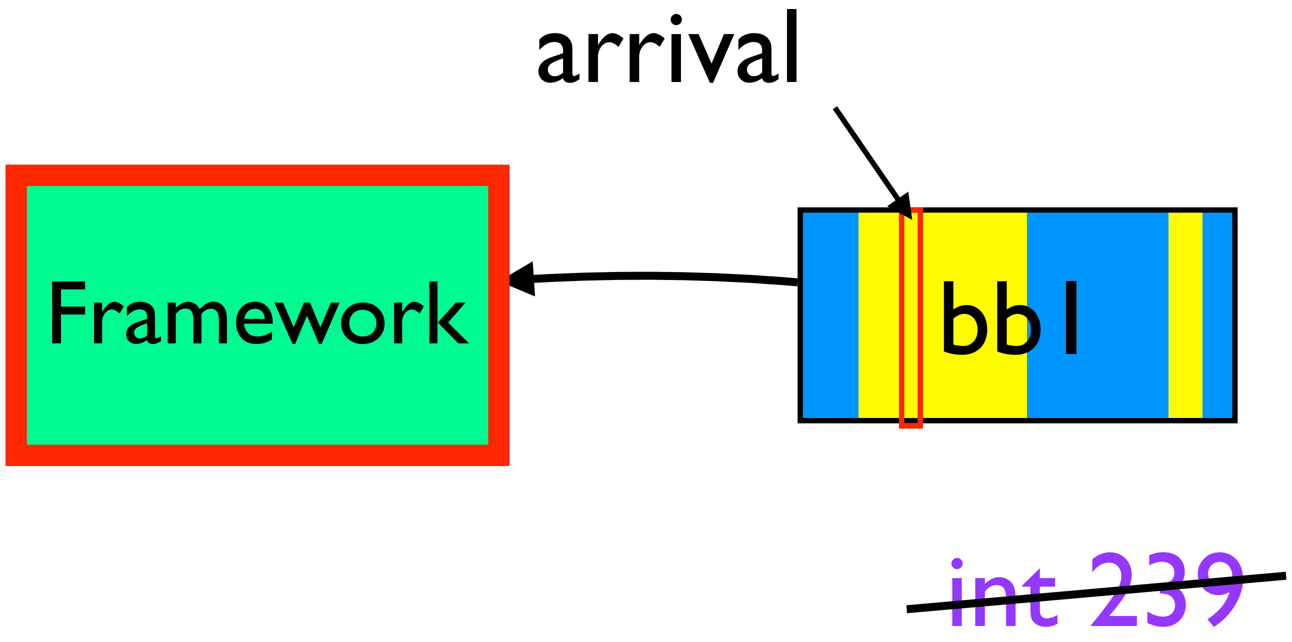
Interrupts enabled	no ~~yes~~
...	

Patch Interrupt Stack Frame

Interrupts enabled	no
...	

Delaying with Patches

Example: interrupt 239



The framework

1. Patches next native instruction
2. Disables interrupts on iret
3. iret
4. Removes patch
5. Enables interrupts on iret

Interrupt Stack Frame

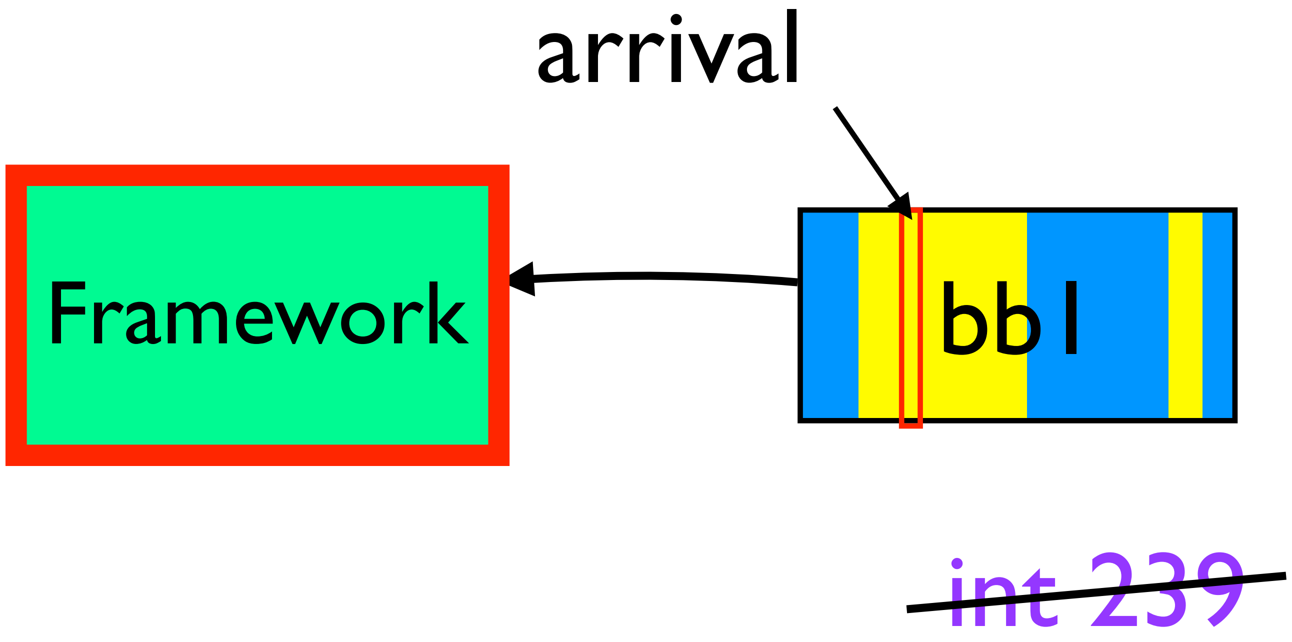
Interrupts enabled	~~yes~~ no
…	

Patch Interrupt Stack Frame

Interrupts enabled	~~no~~ yes
…	

Delaying with Patches

Example: interrupt 239



The framework

1. Patches next native instruction
2. Disables interrupts on iret
3. iret
4. Removes patch
5. Enables interrupts on iret
6. Run instrumented interrupt handler

Interrupt Stack Frame

Interrupts enabled	~~yes~~ no
...	

Patch Interrupt Stack Frame

Interrupts enabled	~~no~~ yes
...	

Delaying with Patches

Example: interrupt 239

The framework

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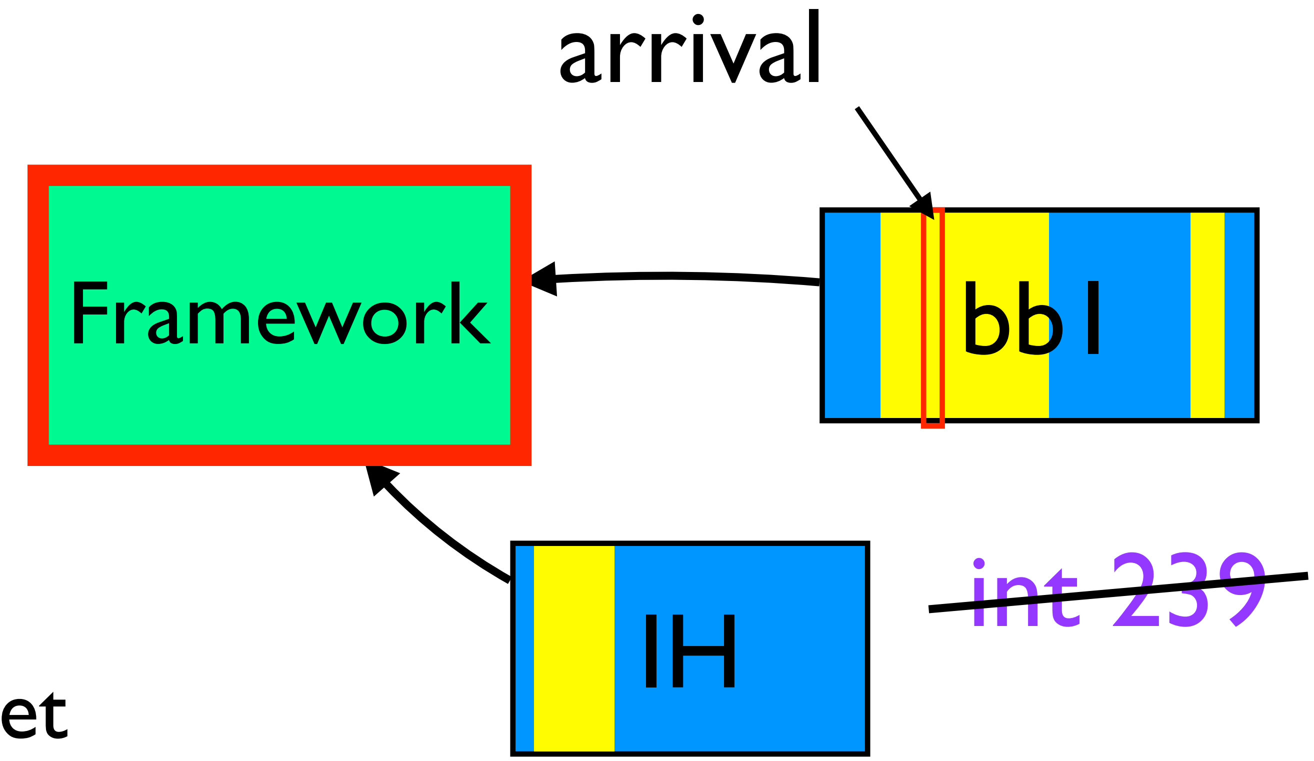


arrival

Framework

bb1

IH

~~int 239~~

Interrupt Stack Frame

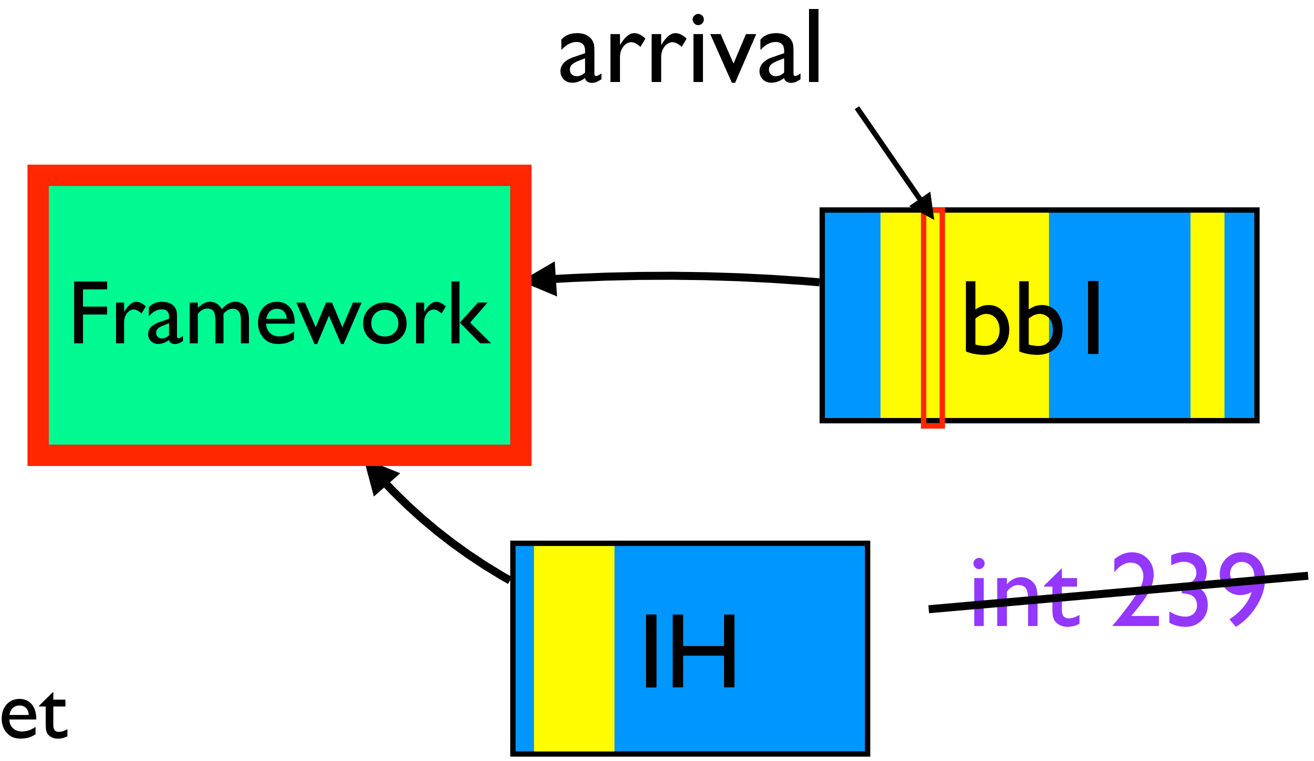
Interrupts enabled	~~yes~~ no
...	

Patch Interrupt Stack Frame

Interrupts enabled	~~no~~ yes
...	

Delaying with Patches

Example: interrupt 239



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Interrupt Stack Frame

Interrupts enabled	~~yes~~ no
...	

Patch Interrupt Stack Frame

Interrupts enabled	~~no~~ yes
...	

Okay, what's the performance?

Performance

Ran framework with instruction counting tool

- Intel Quad Core i7 2.8Ghz, 8GB, 64-bit Ubuntu 10.10

Low application overhead

- JavaScript, Mozilla Kraken: 3% overhead
- Parallel Linux kernel compile: 30% overhead
  - 18% user time increase
  - 143% system time increase

Overhead commensurate with OS activity

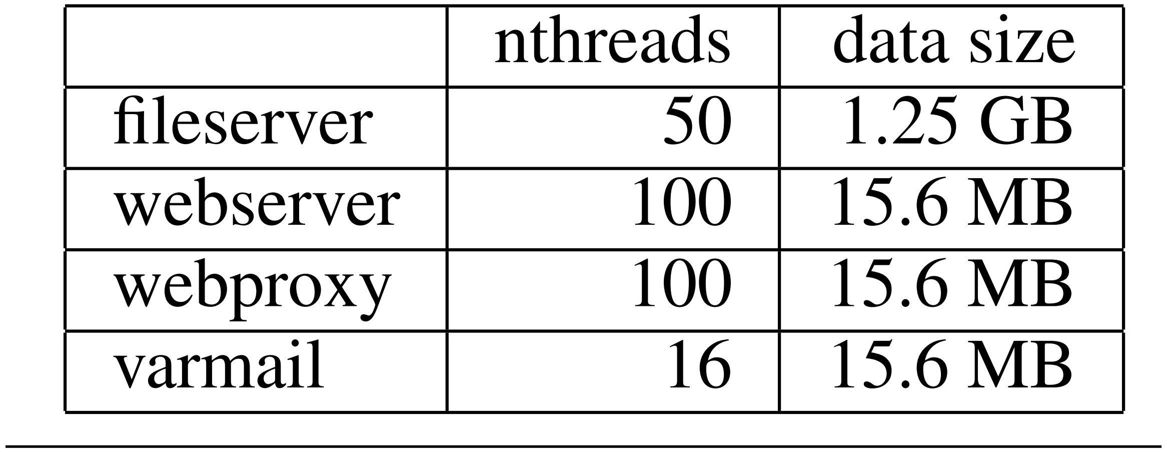
- How bad can this get?

Stress Test Setup

Apachebench and Filebench

Configured benchmarks to stress CPUs and kernel

- Large buffer cache - no disk I/O
- Many threads - lots of context switching
- 100% utilization - shows interrupt processing overhead



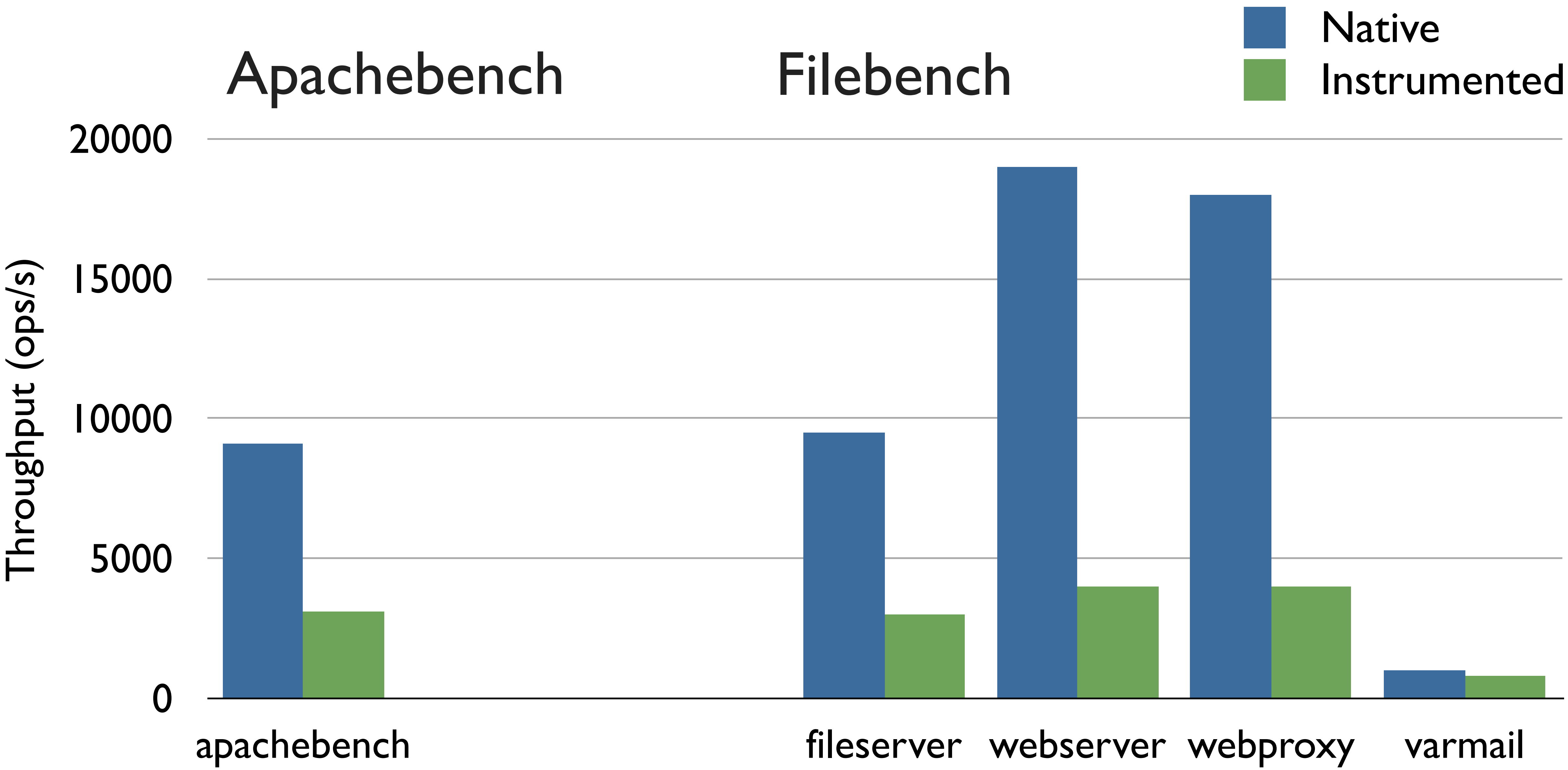
	nthreads	data size
fileserver	50	1.25 GB
webserver	100	15.6 MB
webproxy	100	15.6 MB
varmail	16	15.6 MB

Table 1. Filebench parameters

concurrency level 200

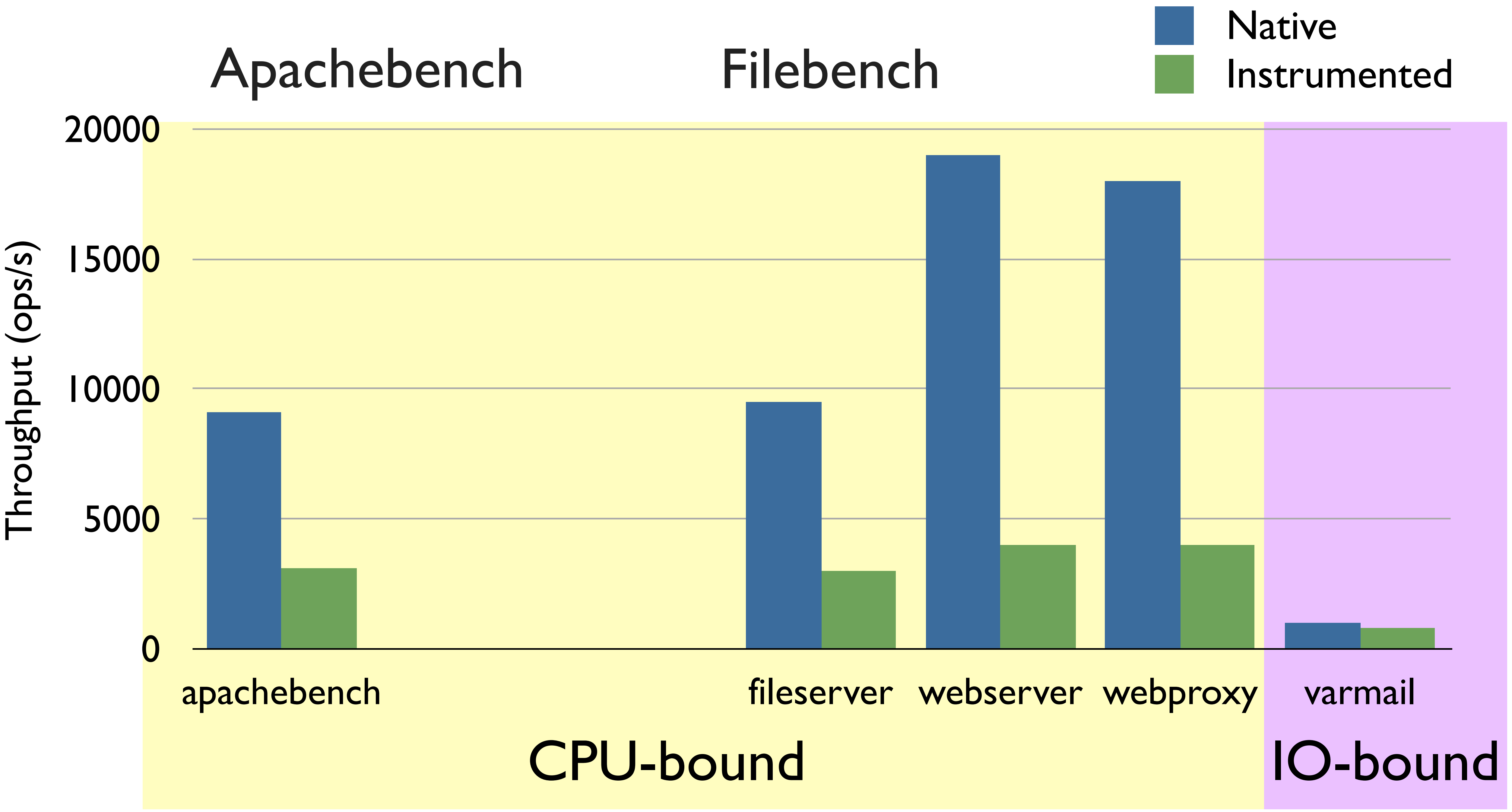
Apachebench Parameters

Stress Test Results



Less than 5x - Reasonable overhead for debugging tools

Stress Test Results



Less than 5x - Reasonable overhead for debugging tools

Summary

Enables dynamic binary instrumentation of OS

Makes it easy to write complex instrumentation

Built useful memory checking tools

Works with arbitrary devices & drivers

Questions?